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A Physical Theory of Electrification

BY

FERNANDO SANFORD
Professor of Physics

WITH TWO PLATES AND ELEVEN TEXT FIGURES

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INTRODUCTION.

The following attempt at a mechanical explanation of some of the simpler phenomena of electrification is due to the opinion that the Faraday-Maxwell theory, based, as it is, upon the assumption of two electricities capable of neutralizing each other's properties, and of attraction as the fundamental phenomenon—making repulsion a special case of attraction—has proved inadequate to explain many of the well known phenomena of static electricity, and has broken down completely in attempting to explain current electricity.

I have tried elsewhere* to show that the physical lines or tubes of force which are an essential part of this theory are incompetent to explain the phenomena for which they were invented, and are inconsistent with our experimental knowledge of facts. It is the purpose of this paper to attempt to show that the mechanical theory of electrification may be greatly simplified by starting with Franklin's theory of a single electricity** and by regarding repulsion, rather than attraction, as the fundamental phenomenon.

Since it is the purpose of this paper to present a physical, rather than a mathematical, theory of electricity, no attempt has been made to state the subject in a mathematical form. The quantitative relations of the electric field have been very satisfactorily expressed both in terms of action at a distance and in terms of lines or tubes of force. It is believed that the equations based upon the notion of lines of force will apply equally well to this presentation of the subject by merely changing the necessary plus and minus signs.

The Electrical Substance.

We have at the present time very definite experimental knowledge of a single electrical substance, divisible into very small particles which are usually associated with other small material particles to make up the ordinary chemical atoms and molecules, but which may exist in bodies in excess of the number actually combined with material particles. I have ventured to call the sub-atoms with which electrons are combined the material part of the atom, as distinguished from the electrical part, because the atomic mass seems to be chiefly associated with this part, and mass is regarded as the material constant of nature.

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*Sanford, Phys. Rev. xxvi, 306, Apr. 1908.

**See note on The Electrical Theory of Benjamin Franklin at the end of this paper.

Electrification.

Electrification was assumed by Franklin to consist of an excess or a deficiency of the electrical fluid (which he sometimes called the "electrical fire") which was assumed to exist as a common stock in the earth and all bodies connected with it. A body was positively electrified when it contained an excess, and a body was negatively electrified when it contained a deficiency of this electrical fire. Applying this definition to our present state of knowledge, we may say that a body is resinously or negatively electrified (using negatively as meaning resinously, and not as indicating a deficiency of the electrical fluid) when if put in electrical contact with the earth or with the inside of a hollow conductor on the earth it will lose electrons, and it is vitreously electrified when if placed under similar conditions it will gain electrons.

In this sense, non-electrification is a relative condition. A body may be non-electrified on the earth, when if moved to another planet it might be electrified.

Since this definition is, in a way, a departure from general usage, it may be well to give it further consideration. On the assumption of two electrical fluids it was supposed that these fluids existed in exactly equal quantities in the earth and in bodies on its surface, and that they were capable when combined of so neutralizing all each other's properties that the existence of either or both could not be detected by any known means. This notion of neutralization has been carried over into the single fluid theory, only here the atoms are regarded as essentially electropositive, just as electrons are essentially electronegative, and it has been assumed that there is just a sufficient number of electrons in the world to neutralize, that is, to render non-attractive and non-repulsive, the atoms of bodies.

This assumption seems to be based wholly on the supposed electrical neutrality of the earth as a whole. If it be possible to show that there is no necessity in electrical theory for such a neutral condition, the argument for equivalent numbers of electrons and atoms falls.

Electrification of the Earth.

If we consider the experimental arguments for or against the equivalent number of electrons and positive atoms, they seem to be universally against such assumption. Even if there were equivalent numbers of the two kinds of charged particles to begin with, there seem to be many reasons why this equivalence could not be maintained.

For example, radioactive changes are taking place on the earth, and apparently in the atmosphere. There are indications that these changes have been more important in the past than they are at the present time. In some of these changes the negative electrons are sent off at very high speeds, and it seems probable that some of them have escaped from the earth.

On the other hand, it seems probable that the earth is receiving electrons from the sun. There are evidences of extensive radioactivity, or at least of extensive disssociation of atoms, on the sun, and there are reasons for thinking that streams of electrons are being discharged from the sun to the earth. The Aurora is generally attributed to a discharge of electrons taking place toward the earth through the very highly rarefied upper atmosphere. No corresponding discharge in the opposite direction is known.

In this connection Sir Oliver Lodge* says: "The earth is in fact a target exposed to cathode rays, or rather to electrons emitted by a hot body, viz., the sun." Again: "The gradual accumulation of negative electricity by the earth is a natural consequence of this electric bombardment extending to greater distances across space, where no residual matter exists; and the fact that the torrent of particles constitutes an electric current of fair strength, gives an easy explanation of one class of magnetic storms; these storms having long been known, by the method of concomitant variations, to be connected with sun spots and aurorae."

The phenomenon of radioactivity, itself, seems to indicate that the electrical conditions on the earth have changed since the present unstable atoms were originally formed. If the atoms consist of electropositive parts combined with electrons, the characters of the groups which constitute the atoms were determined in the beginning by the relative numbers of electrons and positive sub-atoms. If this relation should change with time, certain of the original combinations would become unstable. In fact, the changes which are supposed to occur in the successive disintegration of radium, indicate that there are more alpha particles than electrons set free, even though two electrons are required to neutralize the charge of one alpha particle. Thus, in the complete disintegration series of uranium as given by Soddy,* there are seven alpha particles to four electrons set free. In several changes, only alpha particles are given off. If the atom was neutral before the alpha particle escaped it must have been negatively charged afterward, yet no less than four successive changes of this kind are shown, beginning with the parent of radium and ending with Ra-A.

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*Lodge, Electrons, p. 168.

Aside from the above argument, we have strong experimental proof that the earth is an electrically charged planet. It is well known that the electrical potential rises rapidly with distance above the earth. Within the range of most observations this change is very irregular, though usually in the same direction. This irregularity has been attributed to the irregular distribution of charges on clouds in the earth's atmosphere, which, in order to account for the observed rise of potential must usually be positively electrified. Observations made in the highest balloon ascensions, which are certainly above most of the positively charged clouds, still show a rise of potential which seems to tend toward a constant value. From the sixteen recorded observations on the rise of potential at heights between two and three miles which I have been able to find, the average rise is 10.7 volts per meter. The nine recorded observations above three miles give an average rise of 7.1 volts per meter. Two of these were at heights of approximately four miles, and were respectively 8.4 and 7.9 volts per meter.

These numbers are undoubtedly too small, since in none of the recorded ascensions has there been suitable provision for discharging the balloon. In ascensions to heights of four miles the total rise of potential has been approximately 200,000 volts. If the balloons have retained the electrical charge which they had on leaving the earth, they were about 200,000 volts electronegative to the surrounding air when these highest measurements were made. Since the measurements have regularly been made at a distance of only a few meters below the balloon, the error due to the charge of the balloon has evidently been considerable.

The total change of potential for a height of one mile near the surface, assuming the earth to be an electrified sphere, should be about 1/2000 of the potential of the earth. Assuming the change to be at the rate which has been observed at a height of four miles, the negative potential of the earth would be about 25,600,000 volts. This estimate is undoubtedly of very little value, but it at least indicates that the earth has a negative charge.

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*Soddy, The Interpretation of Radium, p. 205.

If it be assumed that the number of positive sub-atoms in the earth is just sufficient to neutralize the charges of the electrons, then there must be a great excess of positive sub-atoms in the upper regions of the atmosphere to account for the observed rise of potential. The reverse of this seems to be the case, as shown by the great height at which the auroral light has been observed. Hann* gives a number of averages of the height of the auroral light as estimated from a large number of observations by different observers. These averages vary from 35 miles to 140 miles, and Hann regards it as definitely established that auroras may be as much as 125 miles high. Arrhenius† quotes as among the best measurements those of Paulsen, in Iceland, which were made by the use of theodolites at two stations connected by telephone, and which gave the maximum height of the polar light as about 250 miles. The only reasonable explanation yet proposed for the aurora is that it is due to the discharge of negative electrons through the rarefied upper air. This would indicate that the upper limits of our atmosphere are not positively electrified.

Our experimental data accordingly seem to indicate that the earth is not electrically neutral, but that it has a high negative charge which extends at least to the upper limits of its atmosphere.

Nature of the Earth's Electrical Field.

Any hypothesis as to the nature of an electrical field must ultimately resolve itself into one of two possible fundamental assumptions. An electric attraction or repulsion must be either a true action at a distance, or it must be conveyed by an intervening medium. Since the discoveries of Faraday, the second assumption has seemed the only tenable one. Hence all modern electrical theories have been ether theories, and all explanations of static electrical attraction and repulsion have been based upon the assumption of some kind of an elastic stress in the luminiferous ether. This being the case, an electric field is the region throughout which this ether stress may be detected.

It is known from experiment that the electric field about a spherical, charged conductor falls off according to the inverse square law.

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*Hann, Lehrbuch der Meteorologie, S. 4.

†Arrhenius, Lehrbuch der kosmischen Physik, S. 912. See also, Das Werden der Welten, chapter v.

This being true, the ether stress about a sphere as large as the earth would be of nearly the same magnitude on all sides of a small body. That is, if we think of this stress as a pressure exerted by the electrons in the earth upon the surrounding ether, this pressure at a point within the ether would be nearly of the nature of a hydrostatic pressure, so that a small body charged to the same potential as the earth would be under virtually the same pressure in all directions anywhere upon the earth's surface or near the earth.

Elements of Our Theory.

The fundamental assumptions of our electrical theory are, accordingly, as follows:

1. An all pervading ether permeating all known bodies, passing between or through the atoms of bodies.

2. An electric substance consisting of very small particles—electrons or corpuscles—which upon any ether theory must be looked upon as centers of strain in the ether. It is unnecessary to make any assumption as to whether the electron is *only* a center of strain in the ether, but it seems necessary to assume, as has always been done, that the ether in the immediate vicinity of an electron is in a state of strain analogous to an elastic strain in material bodies.

It is immaterial for the purpose of the following discussion what the particular nature of this strain may be if it be allowed merely that it is a strain against which there is an elastic reaction.

3. The material, or, so-called, electropositive constituents of the atoms. These are themselves apparently composed in part of electrons, but whether they consist entirely of electrons or not is a question which is not involved in the present discussion.

4. The earth as a great reservoir of electrons from which all bodies on the earth may draw an unlimited supply, or to which all bodies may give off electrons.

ELECTROSTATIC PHENOMENA.

Electric Repulsion.

If it be assumed that the ether about an electron is in a condition of elastic strain, it necessarily follows that there will be a force of repulsion between electrons. For if a given volume of the ether contain a certain number of electrons, any potential energy which may exist on account of their elastic strain will be a minimum when this strain is uniformly distributed throughout the system, hence the condition of most stable equilibrium will be that in which the electrons are uniformly distributed throughout the ether. This consideration renders unnecessary any further explanation of repulsion, and it makes such explanation impossible without a further description of the character of the ether strain.

But while repulsion alone will tell us nothing further of the character of the electric strain in the ether, the phenomena of radiation enable us to further describe this strain as one analogous to a distorsional, rather than a compressional, strain in a material body.

Properties of the Ether.

Since the ether seems to possess properties analogous to an elastic solid, we may conveniently think of it as being stretched about an electron or a group of electrons just as a rubber balloon or a cavity in an elastic solid may be stretched by forcing into it a fluid under heavy pressure. In an elastic solid, the walls of such a cavity may be both stretched and compressed at right angles to the stretch.

It is not contended that this is the only kind of a strain which will account for the repulsion between electrons, but only that it is one kind which will do so.

Maxwell gave the name Electrical Elasticity to the resistance which the ether offers to an electric strain. This resistance is taken as proportional to the repulsion or attraction between two given electrical charges, and has been shown to be less in all material bodies than in a vacuum, and to be least in metallic conductors. Defined in this way, the electrical elasticity is the reciprocal of the specific inductive capacity.

The ether offers no known resistance to moving electrons or moving charges until their velocity approaches the velocity at which a strain is naturally propagated through the ether.

The ether is the best known insulator of electric charges. That is, electric charges are held to bodies with stronger forces in a vacuum than in any known insulating body.

(In this connection a question suggests itself which seems to be ignored in all attraction theories of electricity. According to the ordinary attraction theory the electrons are drawn to the surface of a negatively charged body by their physical tubes of force running to opposite charges on some other conductor. The pull of these tubes is greater through a vacuum than through any known material dielectric. Electric charges once set in motion in a vacuum move with no appreciable resistance until their velocity is very great. It is generally assumed that there is but one tube of force to an electron, and this is pulling it away from its conductor, but supposing another tube of force, or many tubes of force, to be connected with positive charges within the conductor, still the specific inductive capacity of a metallic conductor is so great that the single tube of force through the vacuum would be more than equivalent to all of them. Why, then, is a vacuum an insulator?)

Electrical Pressure Over the Surface of a Conductor.

Since the ether within a conductor still possesses some electrical elasticity, the electrons within the conductor are still centers of ether strain and accordingly repel each other. At the surface of the conductor this repulsion must be balanced by the stress in the ether outside the conductor. There must accordingly be an electrical pressure exerted upon the surrounding ether by the charge within a conductor. Since electrical charges are free to move about within or over a conductor, the electrical pressure of the ether must be the same over the whole surface of a charged conductor or system of connected conductors when their charges are in equilibrium.

Since the electrical pressure is proportional to the electrical elasticity of the surrounding ether, it must be greater in a vacuum than in any material dielectric. Accordingly, when a charged body is surrounded by a dielectric of high specific inductive capacity, the electrical pressure over its surface is diminished. If it is desired to make the electrical pressure over its surface as great as it was in a vacuum, its charge must be increased. Hence its electrical capacity is said to be increased in a medium of high specific inductive capacity.

Thus, if two equal spheres be connected and charged negatively in air, and then one of them be immersed in paraffin, electrons will flow from the sphere which is in air to the one which is in paraffin, until the electrical pressure becomes equal over the surface of both.

Recapitulation of Fundamental Assumptions.

To recapitulate, we have the following fundamental postulates by which to explain electrical phenomena:

1. An elastic ether, pervading all known space, passing between and perhaps through the atoms and molecules of all bodies; its electrical elasticity being less between the atoms and molecules of bodies than in free space, and relatively much less in conductors than in non-conductors. From the transverse character of light waves and electric waves in the ether, we regard its electrical elasticity as analogous to rigidity in material bodies. We have no data upon its compressional elasticity, but we have reasons for regarding it as very great.

2. We have electrons which, whatever their nature, act as centers of strain in this medium, and on this account, and by virtue of the elastic reaction of the ether to this strain, repel each other. When in free ether and at a distance from material bodies they appear to have perfect freedom of movement.

3. We have the atoms of material bodies which are in part made up of electrons, but of whose structure we know very little.

4. We have the earth containing a sufficient number of electrons, both combined and free, to produce a field of great ether strain around it.

5. On account of the great size of the earth, the electrical pressure in its field becomes nearly a hydrostatic pressure at the surface of the earth, and in closed hollow conductors connected with the earth it becomes a true hydrostatic pressure.

A Conductor Analogous to a Porous Cavity in the Ether.

The conditions of the ether with reference to elastic pressure in the earth's field, and more especially in a hollow conductor connected to earth, are analogous to those of an elastic, nearly incompressible solid, as a jelly or a mass of India rubber, surrounded by a fluid under heavy pressure. A metal sphere or other conductor insulated from other bodies is analogous to a porous cavity in the solid which is under pressure. This cavity may be filled with a fluid under the same pressure as the surrounding fluid, or it may be filled to a greater or a less pressure. These three conditions correspond to Franklin's ideas of an uncharged, a positively charged and a negatively charged conductor, respectively. In our present knowledge of the subject, the one filled to a greater pressure than the surrounding fluid corresponds to a resinously, instead of a vitreously, electrified conductor, as Franklin supposed. The reason that Franklin regarded the vitreously electrified body as the one positively electrified apparently resulted from the accident that he used a glass tube instead of a stick of sealing wax as his source of electrification.

This analogy of a conductor to a porous cavity in the ether is not new. Franklin speaks of matter as "a kind of sponge to the electrical fluid." Sir J. J. Thomson* in discussing the two theories of metallic conductivity, says: "A piece of metal on the first of these theories contains a large number of free corpuscles disposed through its volume. These corpuscles can move freely between the atoms of the metal just as the molecules of air move freely about in the interstices of a porous body. The corpuscles come into collision with the atoms of the metal and with each other, and at these impacts suffer changes in velocity and momentum; in fact, these collisions play just the same part as the collisions between molecules do in the kinetic theory of gases."

If the corpuscles are prevented from escaping from the conductor by the surrounding ether, it follows from the above theory that they must exert a pressure upon this ether corresponding to the pressure exerted by the molecules of a gas upon the sides of the containing vessel. This pressure would vary with the number of corpuscles confined in the metal, and would be greater for a resinously electrified and less for a vitreously electrified than for the normal unelectrified body.

Further Analogy of Electrical Pressure to Fluid Pressure.

In following out the analogy of a conductor to a porous cavity in an elastic solid, let us suppose a block of India rubber to contain a porous, spherical cavity which is filled with a fluid, as a gas, under sufficient pressure to distend the cavity and stretch its walls. If the block be incompressible, its external volume will be increased as much as the volume of the cavity has been enlarged, but the stretching of the rubber around the cavity will cause a pressure perpendicular to the stretching force tending to compress the material about the cavity. If the block be compressible, the rubber will be actually compressed and the external increase in volume will not equal the increase in volume of the cavity. In either case there is a pressure exerted outward normal to the surface of the cavity.

In terms of our ether theory, this corresponds to a resinously charged conductor surrounded by a portion of the elastic ether, say the ether within a room. In order to bring the conditions into closer agreement with our assumptions regarding the ether, it will be necessary to assume that the rubber block is, itself, under external fluid pressure. Thus the ether within the conducting walls of a room is surrounded by the electric fluid within these walls, which is under the normal pressure of the electric fluid within the earth, and which in turn transmits this pressure to the ether which it surrounds.

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*Thomson, The Corpuscular Theory of Matter, p. 51.

It is plain that no matter how great this external hydrostatic pressure upon the block of rubber, and no matter how much the block were compressed thereby, it would have no tendency to drive the distended cavity in one direction more than in another, provided the material of the block were perfectly elastic.

Analogy to An Electrified Body in a Field of Non-Uniform Electrical Pressure.

If the block containing the distended fluid cavity were compressed at one end more than at the other, the external pressure upon the fluid contents of the cavity would be greater on one side than on the other, and the fluid would tend to move into the region of least external pressure.

Thus in Fig. 1, let A represent the distended cavity in the block B D, and place the wedge-shaped weight, C, upon the block. The block will then be compressed at the end, D, and the pressure upon the fluid in A will be greater upon the side toward D than upon the side toward B. If free to move, the distended cavity will be driven toward the end B. In other words, the compressional strain in the block is greater around A and at D than it is at B. Since the condition of least potential energy, due to this strain, will be that in which the strain is as nearly as possible uniformly distributed through the block, there will be an elastic force tending to drive A into the region of least compressional strain, which is toward B.

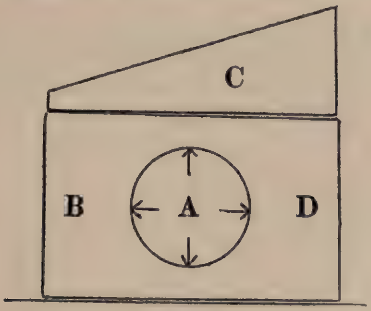

Fig. 1.

The above condition is clearly analogous, on the assumptions of our theory, to a resinously electrified body in a region of unequal electrical pressure.

If we assume a porous cavity in an elastic block under hydrostatic pressure to contain a fluid whose pressure upon the surrounding material is less than the external hydrostatic pressure, the block will be compressed by the external pressure, but its substance will be compressed less than it would be if the fluid pressure within the cavity were equal to the external pressure. If, in addition to the external hydrostatic pressure, the block be more compressed at one end than at the other, as in Fig. 1, the cavity containing the fluid will, if free to move, move into that part of the block which will make the compressional strain most nearly uniform throughout. Since the compressional strain is greatest under the heavy end of the weight and least about the porous cavity A, there will be a force tending to drive A toward D. This is analogous to a vitreously charged conductor in a region of unequal electrical pressure. Accordingly, in a region where the electrical strain in the ether is falling off from a higher to a lower value, oppositely electrified bodies will be impelled in opposite directions by the elastic reaction to this strain. From this principle we may explain all cases of electric attraction and repulsion.

Repulsion of Two Similarly Electrified Bodies.

If the elastic block in our analogy be placed under a true hydrostatic pressure, as in a closed tank filled with fluid under an external pressure, and two spherical, porous cavities, as A and B in Fig. 2, be near together and be filled with fluid under a greater pressure than

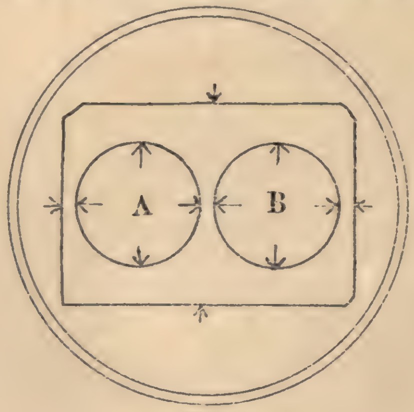

Fig. 2.

the external hydrostatic pressure upon the block, the region of greatest compression will be between the two cavities. Since the elastic reaction to this strain tends to drive each into a region of lower compressional strain, there will be a force tending to separate the two cavities. Thus two resinously electrified bodies in a field of hydrostatic electrical pressure repel each other.

If the two cavities be filled with fluid under a less pressure than the external hydrostatic pressure, as indicated in Fig. 3, each will tend to move into a region of greater compressional strain, and they will tend to separate as before. Thus two vitreously electrified bodies repel each other.

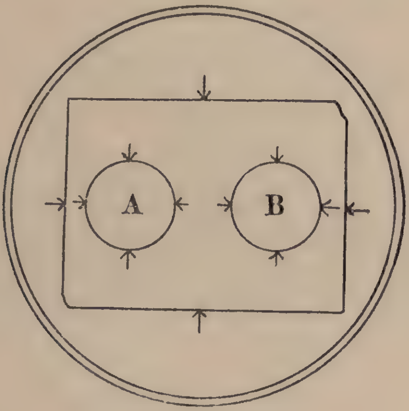

Fig. 3.

Attraction Between Two Oppositely Electrified Bodies.

It follows from what has preceded that if we place within an elastic block under hydrostatic pressure two porous cavities filled with fluid, one to a greater and one to a less pressure than the external hydrostatic pressure, as indicated in Fig. 4, these cavities will, if free to move, approach each other. This corresponds to the attraction between two oppositely electrified bodies.

If the spheres in Fig. 4 are allowed to touch each other, the fluid, or the electricity, will flow from the one in which it is under the greater pressure into the one in which it is under the less pressure until the pressure is the same in both. If after this has occurred the pressure within both is either greater or less than the external hydrostatic pressure, they will again separate.

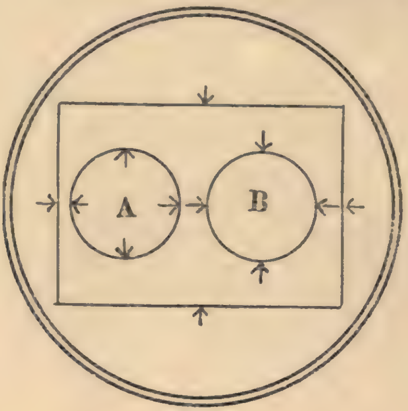

Fig. 4.

Electrical Induction.

If a resinously electrified conductor, as A in Fig. 5, be brought near an unelectrified, insulated conductor, as B, the distribution of the electrical fluid in B will be greatly modified. For example, if another small, insulated conductor, as C, be touched to B at the end a, it will lose electrons to B and become vitreously charged; if the same insulated conductor be touched to B at b, it will gain electrons and become resinously charged, while an intermediate region can be found on B from which C will take no charge of either kind.

If the small conductor be placed at a distance from both A and B and be connected to B by a wire, it will take the same resinous charge, no matter where the wire touches the surface of B. If it be placed near A and joined to B by a wire, it will take the same vitreous charge from any part of the surface of B. If it be placed in the intermediate region where it will take no charge from B by contact, it will take no charge when joined by a wire to any part of B. Accordingly, if the small conductor be joined by a wire to any point on B, it may take, according to its position, a vitreous charge, a resinous charge or no charge at all from B.

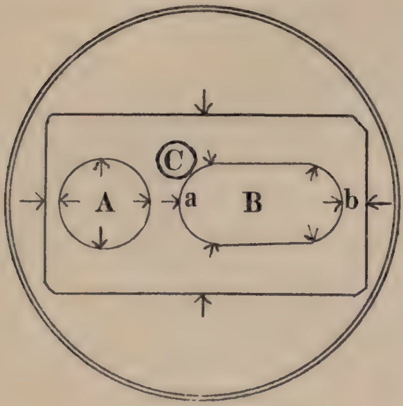

Fig. 5.

If B be connected to earth, the small conductor can no longer take a resinous charge from any part of its surface, but may still take a vitreous charge, which is greater the nearer to A it is when touched to B.

To explain these phenomena in terms of fluid pressure, let A and B, in Fig. 5, be porous cavities in an elastic block under external hydrostatic pressure, and let A be filled with a fluid to a pressure greater than the external hydrostatic pressure, while B was filled with a fluid to exactly the external hydrostatic pressure before it was brought near A. It is easy to see that as B is brought near A the external pressure upon its fluid becomes everywhere greater than the normal hydrostatic pressure, and that this pressure is greatest on the end near A and least on the end farthest from A. Since the fluid in B cannot sustain a different pressure on different parts of its surface, it is driven toward the end farthest from A, while the elastic substance around the end nearest A is stretched inward and made to support a part of the external pressure, as in a cavity which has been filled to less than the external pressure. When equilibrium is established, the fluid pressure in B will be everywhere the same. It will be less than in the elastic block near A, and it will be greater than in the elastic block at a distance from A. There will accordingly be some distance from A at which the pressure in the elastic block will just equal the pressure of the fluid in B.

Suppose another small porous cavity, as C, to be filled with fluid to just the external hydrostatic pressure and to be brought near B. If brought near the end a, its fluid will be under a greater pressure than the fluid in B, and if put in communication with B some of its fluid will flow into B until the pressure becomes the same in both. If touched to B at the end b, it will be in a region of less external pressure than the pressure upon the fluid in B and it will accordingly gain fluid from B. Some intermediate region can be found where the external pressure upon its fluid will exactly equal the pressure upon the fluid in B, and if touched to B while in this position it will neither gain nor lose fluid by the contact.

If placed at a distance from A and joined to B by a tube, it will take the same amount of fluid from B, no matter where the tube joins B. If placed near A and joined to B by a tube, it will lose the same amount of fluid to B, no matter where the tube joins B. If joined to any point on B by a tube and moved about, it will gain or lose fluid according as it is in a region where the external pressure upon its fluid is less or greater than the pressure on the fluid in B.

Charging By Induction.

If an opening be made through the block from B to the outside fluid, some of the fluid will be forced out of B and the fluid pressure in B will become the same as the external fluid pressure upon the block. Under these circumstances, the small cavity, C, would lose some of its fluid if touched to any point on the surface of B, since the pressure within the block due to the increased fluid pressure in A would be greater than the outside fluid pressure for a distance about A greater than the distance to any point of B. There would be no place in the block where the pressure upon the fluid in C would be less than the external fluid pressure, hence there would be no place where fluid would be forced into C from B.

If B, after being put into communication with the external fluid, be again insulated and A be removed, B will be left with less than its normal charge of fluid. This corresponds to the vitreous electrification of a body by induction.

It will be readily seen that if A had been charged with less than the normal quantity of the fluid in the beginning, the pressure in the material medium about it would have been less than the external hydrostatic pressure, and if the above experiments had been repeated the flow of the fluid would have been in the opposite direction each time. Under these conditions, if B had been connected to the outside fluid, some fluid would have entered it, and if it had then been insulated and A had been removed, B would have been resinously charged.

Attraction Between An Electrified and An Unelectrified Body.

It will be seen from the foregoing that when a resinously electrified body, as A, be brought near an unelectrified body, as B, the stress in the elastic medium will be greater around A than around B, and of opposite character. That is, the medium around A is stressed outward, tending to make the cavity larger, while the medium around B is stressed inward, tending to make the cavity smaller. Since the total strain, and accordingly the potential energy due to these two stresses, would be decreased by bringing them together so that they could partly neutralize each other, there will be a force tending to drive A and B together.

The effect of surface curvature upon induction will be discussed later.

The Electric Condenser.

It has been found that when two conductors are placed very close together and one of them is connected to earth, the other will take a much greater electric charge under a given electric pressure than it will when at a distance from other conductors. In other words, its electric capacity has been increased by bringing an uninsulated conductor close to it.

To explain the action of the condenser let A and B, Fig. 6, represent two disc shaped cavities seen edgewise in an elastic block under the hydrostatic pressure of a fluid in a surrounding reservoir. Let B be connected by a tube to the fluid in the reservoir, while A is distended by pumping fluid into it until the pressure inside exceeds the external pressure.

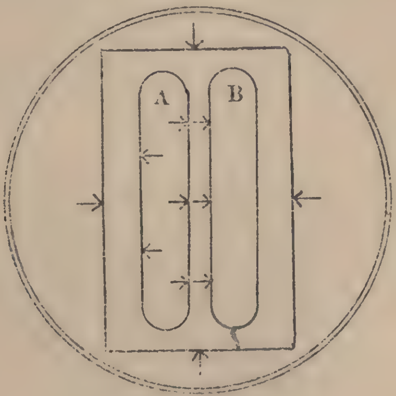

Fig. 6.

Since the pressure on the B side of the elastic sheet between A and B can never be greater than the external fluid pressure, this sheet must support the whole of the excess pressure on the A side by its own elasticity. If the sheet is very thin it will be greatly stretched in supporting a considerable pressure. The result is that the sheet becomes bulged toward B, and fluid is forced out of B almost as fast as it is forced into A. The capacity of A is correspondingly increased, and a much greater quantity of fluid can be pumped into A under a given pressure than could be if B were removed or were not in communication with the external reservoir. It will also be seen that the thinner the elastic membrane between A and B, the more it will be stretched in supporting a given pressure, and consequently the greater the capacity of A.

It is easy to see that if fluid were withdrawn from A, leaving the pressure over its surface less than the normal, a nearly corresponding amount of fluid would flow into B from the outside reservoir, the dividing membrane would be bulged toward A, and the decrease of pressure upon the surface of A would be less than if A stood alone.

Influence of the Elasticity of the Dielectric Upon the Capacity of a Condenser.

It has already been mentioned that the capacity of any insulated conductor depends upon the specific inductive capacity of the medium by which it is surrounded. The same is true of a condenser. If the dielectric sheet between A and B have less electric elasticity than the free ether, it will exert a smaller pressure upon the charge in A than would be exerted by the free ether, and it will accordingly require a greater charge in A to bring its electric pressure up to that of the source from which it is charged than it would if the dielectric were the free ether.

Bound Charge in a Condenser.

Regarding again the condenser in Fig. 6, we have seen that as the fluid is pumped into A the principal enlargement of the cavity A is on the side toward B. The thin membrane separating A and B becomes stretched and bulges toward B.

Suppose that after A has been very much distended toward B the cavity B is disconnected from the external reservoir and A is connected to this reservoir instead. It is plain that some of the fluid in A will flow back into the reservoir, but this flow will cease when the pressure of the fluid on the B side of the membrane plus the pressure due to the contraction of the membrane becomes equal to the pressure in the reservoir. But the pressure on the B side of the membrane was only the reservoir pressure to begin with, and this will fall off as the membrane contracts toward A and the cavity B becomes larger. The result will be that only a part of the excess fluid in A will flow back into the reservoir before the pressure over its surface will equal that in the reservoir. When this condition has been reached, the pressure in B will be less than the reservoir pressure. If now A be disconnected from the reservoir and B connected with it instead, fluid will flow into B until the pressure on the B side of the membrane is equal to the pressure in the reservoir. The pressure on the A side of the membrane will then be greater than the reservoir pressure. Thus by alternately putting A and B into communication with the external reservoir a quantity of fluid will flow out of A each time and a quantity will enter B each time, until the pressure on both sides of the separating membrane becomes equal to the external fluid pressure.

The condition considered above is analogous to the condition known as the ''bound charge'' in a condenser. Thus if two conductors be used and B be joined to earth while A is insulated and charged with an excess of electrons, the dielectric separating A and B will be put into that state of internal stress which is known as the electric field. The electric pressure upon the B side of the dielectric partition can never become greater than the pressure of the earth's field, while the pressure upon the A side may be made very much greater. Accordingly, a quantity of electricity will be forced out of B and into the earth. If B be now insulated and A connected to earth, a quantity of electricity will flow from A to the earth until the electric pressure on the A side of the dielectric membrane becomes equal to the pressure of the earth's field. The electric pressure upon the B side of this membrane will then be less than that of the earth's field, and the dielectric will still be in a state of internal stress. Accordingly, if A and B are alternately one connected to earth while the other is insulated, A will give off electricity to the earth and B will acquire electricity from the earth until the electric pressure on both sides of the dielectric becomes equal to that of the earth's field.

Oscillatory Discharge of a Condenser.

In the case of the fluid condenser of Fig. 6, if after A had become much distended B were disconnected from the external reservoir and the separating membrane were suddenly punctured, the contraction of the walls of A would force the fluid into B with a sudden spurt, and the walls of B would be stretched before the fluid was brought to rest. As soon as the fluid had ceased to flow from A to B the walls of B would contract and spurt some of it back again into A, and the walls of A would be stretched to more than their normal tension. This would continue until the potential energy which was in the stretched walls of A in the beginning had all been transformed into kinetic energy in some form.

It will easily be seen that in the case of the elastic block which we have assumed these oscillations of the fluid would set up waves in the material of the block which would be transmitted in turn to the surrounding fluid. In the case of the unbounded ether, waves set up in this manner would continue to travel outward into space. It is in this manner that the well known Hertzian waves are set up in the ether.

Condition Inside a Charged Hollow Conductor.

It is a well known fact that an uncharged body wholly within a closed, charged, hollow conductor will take no charge from the inner surface. This fact has been regarded as evidence that there is no electricity on the inside walls of a closed, hollow conductor, no matter how great its charge. That this proof is not conclusive may be seen from the following considerations.

Let A, Fig. 7, represent a hollow conductor open at the top and resinously electrified. The excess of electrons in the conductor will exert an electric pressure upon the ether in contact with the surface, both on the outside and inside. If an uncharged, insulated conductor, as B, be lowered part way into A, the part that is within A will be in a field of greater electric pressure than the part outside. The electrons in B will accordingly be displaced toward the end which is outside of A. If B, while in this position, were allowed to come into contact with any part of A, it would take electrons from A, for the outer end of B is still in a region of less electrical pressure than the pressure over the surface of A. If, however, B be lowered into A until it is entirely inside and the opening in A be closed by a conducting cover, B

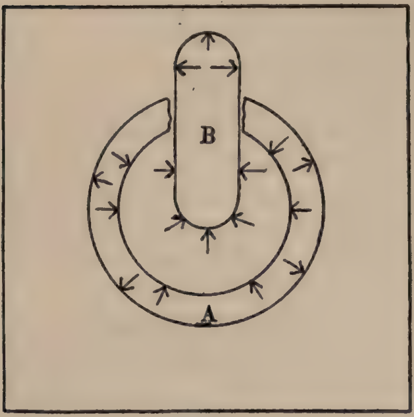

Fig. 7.

will be in a field of uniform electrical pressure exactly equal to the pressure over the inner surface of A. Since the electric stress in a dielectric follows the inverse square law, the pressure upon an electric charge anywhere within A will be equal in all directions, and there will be no reason why the electrons in B should be repelled to one side rather than another. Since the electric pressure is no greater upon a point in contact with A than upon any other point, B may come in contact with A without any of the electrons in A being forced into B. Thus an uncharged body within a closed, hollow conductor will take no charge from the inner surface of the conductor, no matter how great its charge may be.

The same thing will be true when the hollow conductor is vitreously electrified, except that the pressure within the hollow conductor is less than the pressure of the earth's field.

The Charged Body Inside a Hollow Conductor.

Since an uncharged body lowered into a charged hollow conductor can take no charge from the outer conductor, it follows that a charged body lowered into a hollow conductor and placed in metallic contact with it will lose its entire charge to the outer conductor, whether this be charged or uncharged. In the case of an uncharged, insulated hollow conductor the experimental facts are as follows:

If a charged body be placed inside an uncharged, hollow conductor which is insulated from other bodies, an electric field appears outside the hollow conductor as if the charge were on the outer instead of the inner conductor. That is, the electric pressure is everywhere the same over the surface of the outer conductor as if it contained the electric charge. If the inside conductor be now put into metallic contact with the outer it will be discharged, but this will in no way affect the electric field around the outer conductor.

To explain these phenomena in terms of the fluid analogy, let A, Fig. 8, be a porous spherical cavity in an elastic body surrounding a central sphere, B, of the same elastic substance. Let C be a porous cavity in the central sphere B. Let the elastic body which contains the cavity A be under an external hydrostatic pressure. These conditions will correspond in our analogy to a hollow, spherical conductor, A, enclosing another conductor, C. Let A be filled with a fluid to the same pressure as the external hydrostatic pressure, and let C be filled with a fluid to a greater pressure than the external pressure.

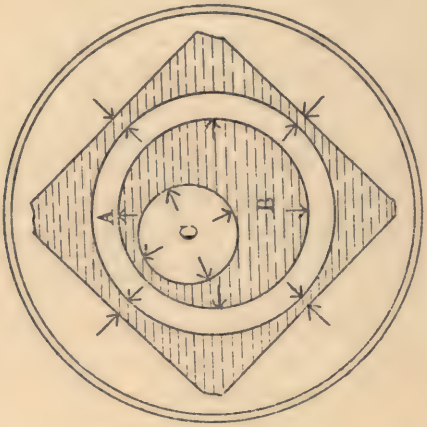

Fig. 8.

The elastic sphere B will then be stretched by the pressure of the fluid in C, and, if perfectly elastic, will transmit this pressure to the surrounding fluid in A, which will in turn transmit it to the elastic material around A. It is plain that if the material of the sphere B is incompressible, the outward pressure of the fluid over the surface of A will be the same as if the same excess of fluid had been forced into A instead of into C. To relieve this external pressure, A may be put into communication with the external fluid, when a quantity of fluid equal to the quantity in C will escape, and the pressure over the outer surface of A will be merely the pressure of the external fluid. When in this condition the excess of pressure in C will be supported entirely by the stress in the elastic sphere B, which will be strained outward. If C be put into communication with A, the excess of fluid in C will flow into A, and the sphere B will again be under hydrostatic pressure. The medium around A will not be affected by this transfer, since there will be the same amount of solid material and the same quantity of fluid inside the outer surface of A that there was before the transfer was made.

This will be equally true if C be allowed to discharge into A before A is discharged. In this case the material of the sphere B is strained outward before C is discharged, and the pressure transmitted by it to the fluid in A causes an outward strain over the outer surface of A. When C is placed in communication with A the outward stress in B is changed to a hydrostatic pressure, thus decreasing the potential energy of strain in B without affecting the strain over the surface of A.

Electric Density.

From the law of inverse squares it appears that the electric pressure is transmitted by the ether without loss, so that if a series of concentric spheres be taken about an electric charge as a center the total pressure over the surface of each of these spheres will be the same. The pressure upon one square unit of the surface of these spheres will accordingly be inversely as the area of the surface. Thus if a sphere of one centimeter radius were charged until the electric pressure over its surface was one dyne per square centimeter, the electric pressure on a surface at a distance of one centimeter from the surface of this sphere would be ¼ dyne per square centimeter.

Let Fig. 9 represent two insulated spheres A and B, the former with a radius of four centimeters and the latter with a radius of one

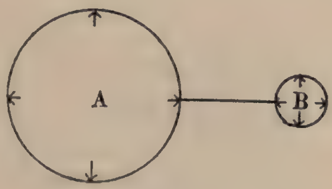

Fig. 9.

centimeter, connected by a conducting wire. Let both be charged until the electric pressure over their surfaces is p dynes per sq. cm. Since they are in communication this pressure will be the same over both. If a distant electropscope be provided with a long wire and the end of the wire be carried over their surfaces, the electroscope will indicate the same electric pressure no matter to what part of the system the wire is applied.

In going out from the two spheres the pressure will fall from p to $\frac{1}{4}p$ at radius distance from the surface of the sphere. Accordingly, around A the pressure falls off $\frac{3}{4}$ of p in a distance of four centimeters, while around B it falls off $\frac{3}{4}$ of p in a distance of one centimeter, or four times as rapidly.

Suppose an insulated sphere one centimeter in diameter to be put in contact with A. The electric pressure at the point of contact is p dynes per square centimeter tending to force electrons from A into the small sphere, while the pressure on the opposite side of the small sphere is 16/25 of p. Electrons will enter the small sphere until the pressure is p over its entire surface.

If the small sphere be brought into contact with B instead of A, the pressure tending to force electrons into it will be the same as before, but the pressure over the side farthest from B will be only $\frac{1}{4}p$. It will accordingly take a greater charge to bring the pressure over the small sphere up to p than it did when in contact with A. The small sphere will accordingly take a greater charge from B than from A.

The fact that a small body will take a greater charge from that part of a conductor where the curvature is greater than from a part where it is less has given rise to the notion that the electricity is more condensed over the more curved parts of the surface. If, however, the small sphere were kept in a fixed position relative to A and B, and were then put into electric contact with each of them by means of a wire, it would take the same charge from B as from A.

Effect of Surface Curvature Upon the Compressional Stress in the Ether Around Charged, Curved Surfaces.

Another fact not heretofore taken into consideration, but which becomes important in this connection, is that for the same fluid pressure in two spheres of different radii the compressional pressure within the elastic medium surrounding the spheres will increase with the radius of the sphere. We know that in the contraction of a curved surface film, as a soap film, the pressure exerted by the film normal to its surface increases with the curvature of the surface. Thus, if a large and a small soap bubble be joined, while the tension in the soap film is the same over both, the pressure of the film upon the contained air is greater in the smaller bubble, and the smaller bubble will accordingly contract into the larger one.

The capillary equation which expresses the pressure normal to its surface exerted by a contracting, spherical film is $P = 2T/R$, where P is the pressure of the film normal to its surface, T the tension of the surface film and R the radius of the sphere.

If instead of the two soap bubbles we had two spherical cavities in an elastic solid, and should pump a fluid into them until the solid around them was stretched, the pressure of the fluid upon the walls of the spherical cavities would be perpendicular to these walls and would be the same in both spheres, but the amount of stretching of the walls produced by this pressure would be different in the two cases. The capillary equation will apply in this case as well as in the case of the soap bubbles, except that the normal pressure P is a constant and the stretching force T varies inversely as the curvature. To express T in terms of the surface curvature we merely transform the capillary equation into the form $T = PR/2$, or T varies as R.

It is well known that a stress which stretches an elastic medium produces an equal compressing stress in all directions at right angles to the stretch. Hence if the walls of the larger spherical cavity are stretched more than the walls of the smaller, they are to the same degree compressed more in a direction normal to the surface of the sphere.

Accordingly, in the case of the two electrified spheres of Fig. 9, if a thin disc or proof plane be applied to the surface of first one and then the other, it will take a larger charge from B than from A, because, no matter how close it is applied to the two spheres, the pressure of the surrounding ether upon its enclosed fluid will be greater around A than around B. In the final limit, if the proof plane were applied very closely to the two surfaces it should take four times the charge from B that it would from A. Accordingly, when tested in this way the surface density of a charge on a system of conductors is said to be proportional to the curvature of the surface on which it rests.

Effect of Surface Curvature Upon Induction.

The compression in the medium surrounding a charged body is shown in another way by the fact that near a charged surface of which the curvature is not great a small body may take a much greater charge by induction than by contact with the charged surface. Thus if an insulated sphere one centimeter in diameter be held at a distance of one centimeter from a charged sphere ten centimeters in diameter and be touched by one end of a wire which is connectd with the earth and again insulated, it will take a charge about four times as great as it will when touched to the larger sphere.

The fact that a body may take a greater charge by induction from a surface of less curvature than its own than it can take by conduction when touched to this surface was shown in some of Coulomb's experiments. Dr. Thomas Thomson* says that Coulomb found that when two spheres of different diameters were charged while in contact and then separated to a small distance, a charge opposite in character to that on the two spheres could be taken from the smaller sphere on the side toward the larger sphere. He found that the greater the difference in the diameter of the spheres the farther apart he could observe this effect. This, of course, means that if the smaller sphere while in this position had been touched to earth it would have taken a charge opposite in character to and greater in magnitude than the charge which it took while in contact with the larger sphere.

I have shown this phenomenon in a striking way as follows: A brass cylindrical vessel eighteen centimeters in diameter, insulated by placing it on a block of paraffin, was connected to a Leyden jar to increase its capacity and was charged from an electric machine. A cylindrical vessel seven centimeters in diameter was placed near the larger vessel and was connected to earth. An insulated sphere one centimeter in diameter was charged alternately by contact with the two cylinders and its charge tested by a gold leaf electroscope which had been calibrated. When the cylinders were four centimeters apart, the small sphere would take from seven to ten times the charge when touched to the small uninsulated cylinder on the side toward the large one than it would when touched to the side of the large charged cylinder. With a larger test sphere the charges taken from the charged and the uncharged cylinder became more nearly equal.

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*Thomson, Heat and Electricity, p. 420.

I have not been able to determine experimentally a quantitative relation between the surface curvature of a charged conductor and the charge which may be induced upon another small conductor placed very near this surface. The sources of possible error in this determination are many, and I have been unable to avoid all of them in any experiment. I have, however, obtained roughly approximate results by several methods. In one case, the two metal cylinders referred to in the former experiment (the one eighteen cm. and the other seven cm. in diameter) were supported twenty cm. apart on paraffin blocks and were connected by a wire and to a charged Leyden jar at a distance of about a meter. For receiving the induced charge, a piece of thin sheet copper 2 cm. long and 1.6 cm. wide was cemented to two pieces of glass rod .4 cm. in diameter and 1.5 cm. long, which were placed parallel and at a distance apart of 1.5 cm. between their centers. A hard rubber handle 16 cm. long was also cemented to the copper plate. When the glass rods were placed against the side of one of the cylindrical vessels a small condenser was formed which had its greatest capacity when the glass rods were parallel to the axis of the cylinder. This is the position in which it was always placed while being charged by induction. While held in this position the copper plate was touched by the end of a copper wire connected to earth, and the induced charges were transferred to a gold leaf electroscope.

The capacity of the small condenser was somewhat greater over the smaller cylinder, as it came somewhat closer to the cylinder, but the determinations gave quite uniformly three charges induced by the larger cylinder equal to five charges induced by the smaller cylinder. This seemed to show beyond any question the influence of the surface curvature of the cylinders upon induction, as otherwise the larger charge should have been induced by the smaller cylinder.

Field Strength and Curvature of Surface.

The strength of an electric field is measured by the force which acts on a unit charge when brought into that field. Since the electric stress in the ether falls off more rapidly around a surface of greater curvature, a small, charged body brought near the charged conductors A and B in Fig. 9 would when near their surfaces be more strongly attracted or repelled by B than by A, since the difference of electrical pressure over its opposite faces would be greater near B than near A.

Electric Discharge Through Air.

When the electric field between two conductors in air becomes strong enough, a spark discharge will take place between them and the conductors will be discharged. This discharge is due principally to the molecules of the air between the conductors being separated into positively and negatively electrified ions and these ions being driven by the electrical field to the conductor having a charge opposite to their own.

What is true of air is also true of other dielectrics. Since their molecules are made up of positively and negatively electrified particles, when the electrical field becomes strong enough their molecules are dissociated and the conductors are discharged by their electrified ions. It is believed that in a perfect vacuum no discharge would take place, even under very great electric pressure.

Electric Discharge From Points.

It has been seen that for the same electric pressure the electric field is stronger over a surface of greater curvature than over a surface of less curvature. Thus in the case of the two spheres in Fig. 9, two small, oppositely electrified conductors would be pulled apart with a greater force if near B than if near A. If B were made smaller and smaller, this separating force very near its surface would become greater and greater. If B were reduced to a fine point, the electrical field very close to this point would be very strong, and might separate the molecules of the surrounding dielectric into their positive and negative ions. If the point were positively charged the negative ions of the molecules would be attracted to it, and would either combine with the metal of the point or give off electrons to the point. In either case the point would be discharged by the surrounding dielectric.

It is well known that a conductor provided with points cannot retain even a very weak charge in air.

Metallic Conductivity.

It is now understood that in the flow of an electric current along a wire the electrons are the only moving particles. There is no proof that the positive parts of the atoms take any part in the transmission of the current. The electrons necessarily move in the opposite direction to the current as conventionally defined, since the direction of motion of the hypothetical positive electricity was assumed as the direction of the current.

There are apparently two possibilities as regards the relation of the conducting electrons to the atoms or molecules of the conductor. They may be electrons which are more or less closely attached to the atoms of the conductor, or the current may be carried by free electrons which move like a wind through a porous body. Sir J. J. Thomson* has discussed both possibilities on the basis of certain assumptions which he has made in both cases, but finds no particular advantage in one assumption over the other, though he seems to have preferred the second alternative. It seems exceedingly probable for reasons which have been given in discussing the earth's field that bodies in the normal electrical condition of the earth do contain an excess of electrons above the number necessary to combine with the positive atoms in their normal condition. We have seen, however, that any great excess of electrons above the number necessary to combine and form the atoms as they are now constituted would cause the positive atoms to take up a greater number. Thus, if all the atoms and molecules in the earth contained just a sufficient number of electrons to make the electrical pressure over their surfaces the average electrical pressure over the earth, they would all be electrically neutral. If, now, the earth could acquire a considerable number of free electrons, so as to increase the electrical pressure over its surface, its atoms and molecules would become electropositive and would require additional electrons to render them electrically neutral. It would accordingly seem that the number of uncombined electrons in the earth must be small as compared with the whole number of atoms or molecules.

It has been shown that the resistance to the passage of an electric current through a conductor is mostly, if not entirely, due to the ether between the atoms of the body. Experiments made by Dewar and Fleming† on the electrical resistance of pure metals and alloys at very low temperatures indicate that the pure metals, with the exception of Bismuth, would become almost perfect conductors at a temperature near absolute zero. Since the absolute zero is supposed to be the point where all molecular vibration would cease, it seems extremely probable that at this point the atoms of bodies would be in permanent contact with each other, and no longer separated by a film of ether. If under these conditions the metals would offer no resistance to the passage of electrons, while the electrons would have to pass through or between more atoms in a given distance than before, it seems certain that the atoms themselves offer no resistance to the passage of electrons. The whole resistance accordingly seems to be due to the ether films which surround the atoms.

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*Thomson, The Corpuscular Theory of Matter, Chapter IV.

†Dewar and Fleming, Phil. Mag. xxxiv, 326, Oct., '92, and xxxvi, 271, Sept., '93.

It necessarily follows from the preceding discussion that if the atoms of a conductor are surrounded by ether whose electrical elasticity is greater than that of the ether inside the atoms, electrons entering an atom will be hindered in escaping from it, just as electrons are hindered in escaping from a conductor, by the greater pressure exerted upon an electron at the surface of the atom by the outside than by the inside ether. This would seem to make it probable that the excess of electrons in a resinously charged body are usually associated with the atoms of the body, and are not free bodies like the molecules of a gas.

Since this view is contrary to the one which seems to be favored by Sir J.. J. Thomson, and which seems to have been adopted by most recent writers on the subject, it may be well to give some of the arguments in its favor which seem to have been generally overlooked.

Bearing of Photoelectric Phenomena on Theories of Conduction.

It has long been known that some metals when negatively charged or when unelectrified give off electricity when illuminated by ultraviolet radiation. This method of producing free electrons is now quite commonly used. The metal most frequently used for this purpose is zinc, but the more electropositive the metal is in the Voltaic series the more readily it parts with its negative charge under the action of the ultra-violet light.

Elster and Geitel* determined the order of photoelectric sensitiveness of the metals, and also found that the effect was associated with the absorption of ultra-violet light by the metals. It is also well known that the arc spectra of these metals contain many ultra-violet lines.

This seems to indicate that the electrons are set oscillating by the ultra-violet light before they are thrown off from the metal, and this hypothesis is strengthened by work done in 1909 by Kunz†. Kunz showed that the intensity of the discharge of electrons from sodium-potassium alloys under the action of ultra-violet radiation varied with the angle of polarization of the incident radiation; that it was greatest when the radiation was polarized at right angles to the plane of incidence, that is, when the electric component of the radiation was approximately normal to the metal surface; and that the electrical discharge was least when the electrical component of the incident radiation was parallel to the surface of the metal. This makes it seem that the electrons which escape from the metal surface are those which have been set in vibration perpendicular to that surface.

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*Elster and Geitel, Ann. d. Phys., xxxviii, 404, 497, 1889; xli, 161, 1890; xlii, 564, 1891.

†Kunz, Phys. Rev., xxix, 174, Aug., 1909.

In later papers* Kunz showed that the velocity of the emitted electrons was independent of the intensity of the incident light, and that their kinetic energy was proportional to the frequency of the incident light. This latter fact has also been shown by others. This shows that the electrons which are set free by ultra-violet light must be in a state of periodic vibration before they leave the metal, and consequently that they are associated with definite atoms, and are not free bodies like gas molecules.

The converse of the photoelectric phenomenon was shown by the present writer first in 1892 and later†. It was found that if a metallic conductor were attached to the cathode of an induction coil while a spark was passed between the terminals, ultra-violet light was sent off from the metal of the conductor. Also, that contact with the cathode was not necessary, but that an insulated conductor placed between the plates of a condenser which were attached across the spark gap of an induction coil while a spark was passed would likewise send out ultra-violet light. Even a hollow metal conductor attached to one of the wires of the spark gap, preferably the cathode, will send off ultra-violet light from its inner surface, and photographs were printed inside a closed tin box by the ultra-violet light sent off by the sides of the box. The wave lengths of the ultra-violet light sent off by different conductors were roughly measured and found to be different for different metals. The same phenomenon has since been examined in this laboratory by Miss Shirley Hyatt for a number of salts and other substances, and so far as they have been tested, only substances which show the photoelectric effect are capable of giving off ultra-violet radiation in the alternating condenser field.

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*Kunz, Phys. Rev., xxix, 226, Sept., 1909, and xxxi, 536, Nov., 1910.

†Sanford, Phys. Rev., ii, 59, 1893; xvii, 441, 1903; xviii, 366, 1904; xxi, 343, 1905.

It would seem that in the case of an insulated conductor in the condenser field the electrons on the surface are set in oscillation by the rapid change in direction of the electric field between the plates, and that these oscillations set up the ultra-violet waves in the surrounding ether. This could not happen unless these electrons were part of an atomic system and had a natural and rapid period of oscillation. It accordingly seems certain that the electrons which are discharged from metals by ultra-violet radiation, as well as those which are capable of setting up ultra-violet radiations around the conductors, are, while in the metals, parts of atomic systems. This being the case, it follows that if these electrons pass along a metallic conductor they do so by means of discharges from one atom to another through the intervening ether films. Since this ether still possesses some electric elasticity within conductors, the successive discharges between two atoms will necessarily be of a periodic character, somewhat as between two conductors in air, except that in the conductor the discharge will be principally in one direction.

Consider the case of two small spheres A and B between two large conductors C and D, as in Fig. 10, one of which is kept negatively and the other positively electrified. Every time a discharge occurs from C to A the ether around A is suddenly stretched, and in its recovery it exerts an increased electrical pressure over A which tends to force the charge onward into B. In a similar manner B passes the charge on to D. The relatively small change in electric pressure over C and D will cause but little oscillation in their electric fields, and consequently but little, if any, of the charge will be forced back from A to C. Also, A in recovering after it has forced its charge onward into B will receive its next charge from C rather than by oscillation backward from B, for A is in an electric field where the pressure is already greater than around B. The discharge along a single line of atoms will accordingly be rather in the nature of periodic flights of one or more electrons in one direction than of the oscillations which accompany an electric spark in air.

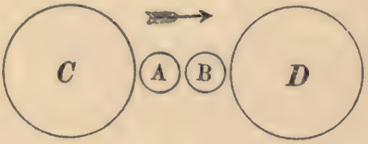

Fig. 10.

This is virtually the method of conduction assumed by Sir Oliver Lodge* and called by him the "fire bucket method." He says in discussing conduction in metals that the atoms, not being susceptible of locomotion, "can only pass electrons on from hand to hand; oscillating a little in one direction to receive them, and in another direction to deliver them up, and so getting thrown gradually into the state of vibration which we call heat."

Surface Currents Along Metallic Conductors.

Since the electric elasticity of the ether between the atoms is very slight, the oscillations of a discharging atom will be relatively slow. The electrons will accordingly be passed from one atom to another much more slowly than in the case of the electric spark in air. Over the surface of a conductor there will necessarily be a surface film of atoms in which the ether elasticity changes from that of the surrounding dielectric to that within the interior of the conductor. Since the average electric elasticity of the ether in this surface film is greater than the electric elasticity of the internal ether, when a current is being set up in a conductor the electrons will be passed along more rapidly on the surface than in the interior. For this reason an alternating current of high frequency is confined principally to the surface of the conductor. It is very probable that the carrying power of a conductor for such currents will be different in dielectrics of different specific inductive capacity.

Influence of Surrounding Dielectric Upon Conductivity.

It seems probable, also, that after a current is established in a conductor the influence of this surface film may still be felt, especially in fine wires, where the surface film becomes a measurable part of the cross section of the conductor. In this event, the carrying capacity of a fine wire even for direct currents might vary in different dielectrics. This phenomenon was observed by the writer in 1891† and was verified by Grimaldi and Platania at the University of Catania in 1895‡.

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*Lodge, Electrons, p. 107.

†Sanford, Some Observations Upon the Conductivity of a Copper Wire in Various Dielectrics. Leland Stanford, Jr., Publications, 1892. See also Phil. Mag. xxxv, 65, 1893; Phys. Rev. iii, 161, 1895.

‡Sulla Resistenza Elettrica Dei Metalli Nei Diversi Dielettrica. Memoria di Giovan Pietro Grimaldi e Giovanni Platania, Catania, 1895.

In regard to this phenomenon the conclusions of different observers have been conflicting, and in my own observations certain wires failed entirely to show the effect. This, I think, is due to the formation of a dielectric film over the surface of the wires in some cases, which film does not change when the dielectric surrounding the wire is changed.

Heating Effect of Current.

The periodic discharges of electricity from atom to atom as assumed above would cause oscillations of the atoms, themselves. When two contiguous atoms have unlike charges they attract each other, when like charges, they repel each other. Accordingly, each discharge will produce a vibration of the atoms. Since the distance through which the atoms of a conductor can vibrate is fixed within narrow limits, and since there must be one vibration for each discharge, the velocity of the vibrating atoms will vary as the rate of discharge between them, and accordingly as the current intensity. The energy of atomic vibration will accordingly vary as the square of the current intensity.

Ether Radiation About a Current.

Since each atomic discharge causes at least one stretching and one contraction (in terms of our analogy) of the ether about the atom, the ether about a current flowing in a conductor will be in a continuous state of periodic agitation. These periodic agitations will set up waves in the internal ether which may spread to the ether surrounding the conductor. On account of the relatively slow rate of discharge due to the slight electric elasticity of the ether surrounding the atoms, these waves will be of lower frequency than light waves. They are probably associated in some way with the magnetic field about a current.

Relation of Heat Conductivity to Electrical Conductivity.

Since atoms are built up of oppositely electrified particles, unless the total charges of both kinds are equal and concentrically arranged, each atom must have an external electrical field. It will be shown later that the attraction due to these electrical fields between atoms constitutes cohesion.

If an atom be set oscillating, the electrical field between it and surrounding atoms will vary periodically. Accordingly if the atoms at one end of a conductor be thrown into oscillation, these oscillations will be transmitted to all the atoms in the conductor by the periodic variations of the electric fields between them. The greater the electric elasticity of the internal ether and the closer the atoms are together the faster this disturbance will spread through the conductor. The same conditions in the surrounding ether which would make an atom pass its charge along quickly will make it transfer its energy of vibration rapidly. Good conductors of electricity should accordingly be good conductors of heat.

Contact Electromotive Force.

It was shown by Volta, in 1801, that when two plates, one of zinc and one of copper, provided with insulating handles are brought into contact with their faces parallel to each other and then separated, the zinc becomes vitreously and the copper resinously electrified. Volta also showed the same conditions to hold with a number of other metals, and he arranged a series of metals in which each metal becomes positively electrified when brought into contact with one below it in the series.

Volta's experiments have been frequently repeated, and several series of careful measurements of contact electromotive force have been made, notably by Lord Kelvin and his students and by Pellat. It has also been shown by Righi and by Majorana* that "Whenever two dissimilar conductors after having been discharged to earth approach each other without being brought into contact, they acquire free electric charges which may be removed by any conductor (not an electrolyte) whether put to earth or insulated, but in the latter case the conductor must be of large capacity relatively to that of the disks experimented upon.

"These *approach charges* are opposite in sign to those obtained in the ordinary Volta experiment; so that zinc brought near to copper is charged negatively, and copper brought near to zinc becomes positively charged."

Volta believed this contact electromotive force to be between the metals, themselves, and to be a true property of the metals. Others have held to the theory that the observed electromotive force is due to chemical action taking place between the metal and the surrounding medium, probably the oxygen of the air. The modern chemical explanation is usually somewhat as follows: The metals are covered by an adsorbed water film. This water film contains oxygen from the air, and consequently oxidizes the surface of the metal, making a solution of the metallic oxid. This, when dissolved in water, dissociates into positive (metallic) ions and negative hydroxid ions. The negative ions have the greater diffusion velocities in the solution, and hence move away from the plate faster than the positive ions. Hence when two metals are placed in contact the more oxidizable metals lose their negative ions faster than the nobler metals and consequently become more positively electrified.*

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*Q. Majorana, Phil. Mag. xlviii, 241 and 255, Sept., 1899.

This explanation fails utterly to account for the "approach charges" referred to by Majorana. The total possible distance of separation of the two kinds of charged ions in the electrolyte, assuming only one of them to diffuse into the liquid at all, would be less than half the thickness of the adsorbed water film. That is, if the metallic ions did not diffuse into the water at all, and if their attraction for the hydroxid ions were zero, after they had become uniformly diffused throughout the liquid film their average distance from the metallic ions would be half the thickness of the liquid film. Of course, such a supposition as this is untenable, and their average distance from the positive ions must be very much less than this. It would accordingly be inconceivable that the electric fields which have been observed between metal plates could be produced in this way, even if the surface layer of ions were positive over one metal and negative over the other. But from the fundamental assumptions of the theory the surface ions over both plates are negative. The presence of each would accordingly weaken the electric field of the other.

Not only does the above hypothesis fail to explain the phenomena for which it was invented, but the conditions assumed in it seem to have been excluded in experiments made by Mr. J. Erskine-Murray† and Mr. F. S. Spiers‡. Erskine-Murray found that plates whose surfaces had been prepared by filing or scraping under melted paraffin, or by melting the metal and pressing between glass plates kept all the time under melted paraffin, and whose surfaces had never been exposed to the air, gave sensibly the same contact difference as when prepared in air. He also found the contact difference of potential to vary with the temperature, each metal having its own temperature coefficient of variation, but all varying in such a way as to suggest that at a low temperature (somewhere below —200° C.) all contact differences would disappear.*

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*See Knoblauch, Zeit. für phys. Chem., xxxix, 225.

†Erskine-Murray, Phil. Mag., xlv, 398-432, 1898.

‡Spiers, Phil. Mag., xlix, 70, 1900.

Spiers found that iron and platinum plates which had been heated red hot for some time in a hydrogen atmosphere and in a very low vacuum still showed a contact difference of potential of .6 volt, but in this case the iron was negative to platinum while under ordinary circumstances it is positive. Mr. Spiers argues the impossibility of removing the last trace of oxygen from the space surrounding the metals, but certainly the adsorbed water film must have been removed in both his experiments and those of Erskine-Murray.

As regards the existence of the phenomenon under consideration there can be no question. The difference of opinion is upon the adequacy of Volta's explanation. From the point of view adopted in this discussion, the contact difference of electric potential would follow from the fundamental assumptions.

Thus, electric charges move about within conductors or from one conductor to another as a result of an ether pressure upon their electrons. This pressure, which is due to the electric elasticity of the ether, is less in all bodies than in the free ether, and is less in conductors than in other bodies. We have seen, however, that the atoms of conductors are apparently surrounded by ether films, and that the electrons are held to the positive parts of the atoms by the electric pressure of these ether films. Hence all bodies, even conductors, have some electric elasticity in their internal ether.

When electrons are forced into a conductor from the earth, which serves as a great reservoir in which the electric fluid is stored under pressure, they are resisted by the electric pressure of the earth's field over the surface of the conductor, and by the electric elasticity of the ether films surrounding the atoms within the conductor. The greater the ether elasticity between the atoms of the conductor, the larger the part of the electric pressure of the fluid in the earth it will support. The less the electric elasticity of the ether within a conductor, the greater the pressure which the charge it takes from the earth will exert upon the ether in the surrounding dielectric. If two conductors have slightly different internal ether elasticities, the charges which they take from the earth will exert slightly different pressures upon the ether surrounding them.

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*The significance of this observation will appear, if it be shown that the contact potential difference depends upon the elasticity of the inter-atomic ether, since at absolute zero the atoms may be assumed to be in contact.

If two such conductors be insulated from the earth and brought near together, since the electrons within one exert a greater pressure upon the surrounding ether than do those within the other, there will be an electric field between them. Since the ether pressure is greater over the surface of the one having the smaller internal ether elasticity (hence the greater specific inductive capacity) this one will be negatively electrified relatively to the other. If the conductors are brought into contact with each other, since the charges in the two bodies previously exerted different pressures upon the surrounding ether, their reciprocal pressures upon the surface of contact will be different. There will be an unbalanced pressure across this surface, and electricity will flow from the one which exerted the greater pressure upon the surrounding ether into the one which exerted the smaller pressure. This one, if insulated from the other and connected to the earth, will then be found to have a resinous charge with reference to the earth.

To produce the corresponding phenomenon with material bodies, let A and B, as in Fig. 11, represent two porous cavities in a block of India rubber, and let the tissue separating the porous spaces be thicker or more elastic in B than in A. Let both cavities be put into communication with the same reservoir containing a fluid under pressure. When the fluid is forced into both cavities its pressure will be supported partly by the elasticity of the rubber tissue surrounding the porous spaces inside the main cavities, and partly by the surrounding rubber. Since this porous tissue has a higher elasticity in B than in A, the rubber surrounding B will be stretched less than that surrounding A.

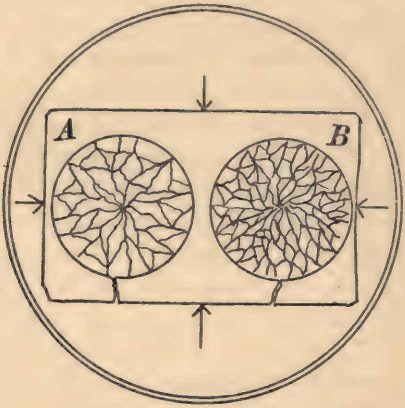

Fig. 11.

If the two cavities be disconnected from the reservoir and brought very near together, there will be a falling off from A to B in the internal stress of the rubber immediately between them. This corresponds to the falling off of electric stress in an electric field, and is analogous to the Righi-Majorana phenomenon. If while still very close together the two cavities be put into communication with each other, fluid will flow from A to B until the elastic strain is equalized over both sides of the elastic membrane separating them. This corresponds to the Volta phenomenon.

If the porous cavities are in the shape of flat discs and their plane faces are brought close together the region of varying strain between them will be much greater than if they are spherical, and accordingly a much greater quantity of fluid must flow from the one to the other before this strain becomes hydrostatic.

This view of the phenomenon would make the Volta contact series in metals the same as the dielectric series. That is, the conductor around which the electric fluid received from the earth exerts the greatest pressure is the one having the least internal electric elasticity and the greatest specific inductive capacity. It is also the one which would lose electrons when insulated from the earth and brought into contact with a conductor having a lower specific inductive capacity.

This law has already been observed for non-metallic substances. In 1898 Coehn* announced that for non-metallic substances those having a higher dielectric constant become positively charged when brought into contact with substances having a lower dielectric constant. Consequently the explanation of contact electromotive force here given will apply equally well to conductors and non-conductors.

Contact Electromotive Force and Cohesion.

We have seen that the parts of the atoms in material bodies are held together by electrical forces resulting from the electrical elasticity of the ether surrounding these atoms. The same must be true of the forces which hold together the individual atoms in a solid or a liquid. That is, the electropositive sub-atoms must be held together by the mutual attraction of two or more of them for the same electron or electrons. This attraction when it holds together the atoms of a gas molecule is called chemical affinity, but when it holds together the atoms or molecules of a solid or liquid is generally called cohesion.

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*Coehn, Wied. Ann., lxiv, 217, 1898.

Since cohesion is the attraction between positively and negatively electrified particles it must depend, among other things, upon the electric elasticity of the ether surrounding these particles. In bodies of similar atomic structure, as in the pure metals, cohesion should be greater when the internal elasticity of the ether is greater, and consequently when the specific inductive capacity is less.

We have already seen that from our argument the greater the internal elasticity of the ether the more electronegative the metal should be in the Voltaic series. From what has been said regarding cohesion, it would seem that the cohesion series of the metals should be the same as the Voltaic series, the metals with least cohesion being the most electropositive. That this law seems to hold with very few exceptions was shown by the present writer in a paper prepared for the meeting of February, 1908, of the American Physical Society.* The following table is taken from this paper.

VOLTAIC SERIES	Compressibility x 10^6	Melting Point	Expansion Coefficient	Hardness
Caesium	61	26.5		.2
Rubidium	40	38.5		.3
Potassium	31.5	58		.5
Sodium	15.5	95	.000072	.4
Lithium	8.8	180		.6
Zinc	1.5	419	.000029	2.5
Lead	2.2	330	.000028	1.5
Tin	1.67	230	.000022	1.8
Iron	.38	1500	.000012	4.5
Silver	.82	950	.000019	2.5—3
Copper	.54	1054	.000017	2.5—3
Gold	.47	1035	.000015	2.5—3
Platinum	.21	1780	.000009	4.3
Carbon	.5	unmelted	.000005	10.

*Sanford, Phys. Rev. xxvi, 410, 1908.

Since there are no direct data on the cohesion of the metals, I have attempted to relate the Voltaic series to the compressibility, the melting point, the expansion coefficient and the hardness, using the metals whose positions in the Voltaic series are fairly well known. The data on the melting point, the expansion coefficient and the hardness are taken from Landolt and Boernstein's Tables; the compressibilities are taken from an article by Professor T. W. Richards, in *Zeitschrift fuer physikalische Chemie, LXI,* 196, *Dec.,* 1907. Since writing the article referred to above, I have found in *Beiblaetter XIV*, 705, 1901, a reference to an article in Russian by N. Hesehus, in which he has related the contact electromotive force of metals to the hardness on experimental grounds. This article was unknown to me when I wrote the paper for the American Physical Society.

As will be seen from the table, iron seems to form the one important exception to the law. Its other properties would make it seem to belong just above platinum in the Voltaic series. In this connection it is interesting to recall the fact that Spiers found iron, when heated a long time in an atmosphere of hydrogen to get rid of oxidation, to be electronegative to a platinum plate which had been heated with it in the hydrogen. It is not likely that the true electromotive force between iron and platinum was determined by this experiment, since both metals absorb hydrogen readily when heated, so that their specific inductive capacity was probably affected by the dissolved hydrogen, but it makes it seem probable that the two metals belong much closer together in the Voltaic series than previous experiments have indicated.

Zinc also seems to be out of place in the series as indicated by all the properties considered except its expansion coefficient. In some of the determinations which have been made zinc falls below lead in the series, but its compressibility and its melting point would seem to place it between tin and silver. Since Erskine-Murray, in the paper previously referred to, found zinc and lead to have positive temperature coefficients and tin to have a negative temperature coefficient of electromotive force, at a lower temperature tin would come above both lead and zinc in the series.

Since the publication of the above table a reference in *Science Abstracts, Section A, No.* 139, *July* 26, 1909, *Abstract* 1158, states that I. Traube "has recently shown that if, by means of van der Waals' equation the approximate surface tensions, $a/v^{2/3}$, are calculated, it is found that the numbers and the electric potential-difference of the metals, and therefore the Voltaic series, corresponds extremely closely.'' Since the surface tension is definitely dependent upon cohesion, this furnishes another strong proof of the hypothesis that both are dependent upon the electric elasticity of the internal ether.

Temperature Coefficient of the Volta Electromotive Force.

Erskine-Murray, in the paper already cited,* has given a few determinations of the variation of the Volta electromotive force with temperature. He found that the metals aluminium, zinc and lead become more positive as the temperature increases while iron and gold become more negative. In silver, copper and tin the change is very slight.

Since from our hypothesis the position of the metal in the Voltaic series depends upon the specific inductive capacity of its internal ether, this would indicate that in aluminium, zinc and lead the specific inductive capacity is increased by an increase of temperature, while in iron and gold it is decreased. Since the specific inductive capacity of a metal is apparently not measurable, it is impossible to verify or disprove this hypothesis by direct experiment.

The Seebeck, Thomson and Peltier Effects.

Other phenomena which are apparently associated with the change of electromotive force with temperature are the Seebeck effect, the Thomson effect and the Peltier effect. Thus if a circuit be composed of two metals which occupy different positions in the Voltaic series electrons will flow from one metal to the other at both junctions until the Volta difference of potential is neutralized by an excess of electrons in one metal and a deficiency in the other. There is then no reason why electrons should flow in one direction more than in the other at either junction. If, however, one junction be warmer than the other and if one metal have a different temperature coefficient of electromotive force from the other the pressure upon the electrons will be no longer balanced at the two junctions and a Seebeck current will flow around the circuit. This current will flow in a direction such that the electrons acquire energy from the atoms at the hot junction and return it again to the atoms at the cold junction, but the mechanism by means of which this transfer of energy is accomplished is not understood. From the hypothesis advanced in this paper, atoms surrounded by ether having a higher electric elasticity should discharge their electrons at higher velocities than atoms surrounded by either having a lower electric elasticity. Accordingly, when atoms of the former kind discharge their electrons into atoms of the latter kind, the electrons should enter the atoms with a higher velocity than they would have on leaving them, and should accordingly give some of their kinetic energy to the atoms. It is difficult to see in what other way an energy exchange could take place between the atoms and electrons. Too little is known at the present time, however, concerning the temperature coefficient of the Volta effect and the magnitude of the Seebeck, Peltier and Thomson effects in the same metals to explain the phenomena on the above hypothesis or on any other grounds.

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*Erskine-Murray, Phil. Mag., xlv, 398-432, 1898.

The Thomson effect would seem to follow directly from the change in the Volta electromotive force with change of temperature, but the question of the exchange of energy between the electrons and atoms offers the same difficulty of explanation here as in the Seebeck and Peltier effects.

ELECTRIC CURRENTS.

Electrolysis.

We have seen that cohesion between the atoms of a metal is an electric force. The only kind of electric attraction we know is the attraction between opposite electrical charges. The only negative electrical charges known to us are the electrons. Hence cohesion must be the attraction between positive sub-atoms and electrons. Such an attraction would not hold atoms together unless two or more positive sub-atoms were attracted by the same electron. Hence cohesion or affinity must consist of the mutual attraction of two or more positive sub-atoms for the same electron or electrons.

Electric attraction varies inversely as the specific inductive capacity of the medium around and between the charges. Since the specific inductive capacity of the surface film of metals must be less than that of the interior, cohesion must be greater between the surface atoms than between those of the interior.

This cohesion of the surface film must vary with the electric elasticity of the surrounding ether, consequently when a metal is immersed in a medium of high specific inductive capacity the cohesion between its surface atoms must be diminished. The specific inductive capacity of water is 80, hence when a metal is immersed in water the electric pressure which holds the surface atoms to the metal is 1/80 as great as before. If with this weakening of the surface cohesion there is combined a cohesion between the positive sub-atoms of the metal and the water molecules, or between the positive sub-atoms and negatively charged ions contained in the water, the positive sub-atoms of the metal may break away and escape into the water.

The mere weakening of the surface cohesion by water is not alone sufficient to dissolve metals extensively, but the specific inductive capacity of mercury is so great that many metals go into solution in it. When water contains negatively charged ions which attach themselves to the positive sub-atoms of the metal and in that way weaken their attraction for the electrons in the metal, most metals may go into solution in water.

What is true of the surface atoms of metals is also true of other solids. In many solids the chemical molecules are held together by much weaker forces than are the positive sub-atoms and electrons in metals, and these substances frequently go into solution in water. If the substance be one having a lower specific inductive capacity than water, its chemical molecules are held together by weaker forces when dissolved in water than they were before solution, hence many molecules which are stable in the solid or liquid form or as gas molecules become unstable when dissolved in water, and dissociate into positively and negatively electrified sub-molecules, called ions. Alcohol, with a specific inductive capacity of 25 ranks next to water, but far below it, as a general solvent.

This molecular dissociation in water solutions is especially marked in mineral acids, bases and salts. Most mineral acids seem to be made up of molecules consisting of one or more electropositive hydrogen sub-atoms held to another positive sub-atom or group of atoms by their mutual attractions for one or more electrons. When these complex molecules are dissolved in water, the electric attraction between their positive and negative parts is so weakened that the hydrogen sub-atoms break away from the connecting electrons and become positive ions, while the remaining positive sub-atom or group of atoms retains the connecting electron or electrons and with them constitute the negative ions.

In all the common acids the weakest attraction seems to be between the hydrogen sub-atoms and the connecting electrons. This must mean that hydrogen is less strongly electropositive than the other atom or group of atoms with which it is associated in the molecule. Thus if the positive sub-atoms be themselves made up of positive and negative particles, the charges of these particles must be more nearly balanced in hydrogen than in the other sub-atoms with which it is associated in acids. When metals go into solution their ions, being more electropositive than the hydrogen ions already in the solution, form more stable combinations with the electronegative ions of the solution and tend to permanently displace the hydrogen sub-atoms. This indicates that the positive charges of the metallic sub-atoms are not exactly equal to, nor exact multiples of, the hydrogen sub-atom, as has been assumed in all modern electrical theory.*

Those metals in which cohesion has been shown to be weakest are the ones which most easily give off their positive sub-atoms to the electrolytic solution. Since the electrons which were associated with these positive sub-atoms are left behind in the metal, the undissolved part of the metal becomes more and more electronegative as its positive ions escape. If the metal be insulated, it may become sufficiently electronegative to hold its positive sub-atoms from further escaping into the solution. Since the more electropositive metals give off their positive sub-atoms faster than the others, they become electronegative in the solution faster than the others. Accordingly, the weaker the cohesion in a metal the more electropositive it is in the Voltaic series and the more electronegative it becomes in the electrolytic series.

The Voltaic Cell.

If plates of two metals, as zinc and copper, be placed in an acid water solution both give off positive sub-atoms to the solution. Since cohesion is greater in copper than in zinc, zinc dissolves more rapidly than copper, and hence becomes more rapidly electronegative. If the two metals be connected by a wire some of the electrons set free in the zinc will flow along this wire to the copper, thus keeping both metals at the same electrical potential. Copper will accordingly become strongly enough electronegative to hold its positive sub-atoms before the zinc will. As the zinc continues to give off its positive sub-atoms to the solution and its negative electrons to the copper, the latter soon acquires a sufficient negative charge to attract to it the positive ions of the solution. If these are metallic ions, they are deposited upon the copper plate, combining with some of the electrons in the metal and making it less electronegative. If they are hydrogen ions, they are attracted to the plate and probably enter it, after which two of them combine with one or more electrons and, being no longer held by the plate, escape as hydrogen gas molecules.

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*The question of the relative magnitude of atomic charges will be discussed at greater length later.

The zinc will accordingly continue to give off positive sub-atoms to the solution and negative electrons to the copper, while the copper receives negative electrons from the zinc and positive ions from the solution. The electric current in the solution will be due, on the whole, to the drifting of positive ions from the zinc to the copper, while the current in the connecting wire will be due to the drifting of electrons from zinc to copper. Dissociation will be continually taking place at the surface of the zinc and recombination will be taking place at the copper surface. The source of energy in the Daniell's cell is accordingly the difference of cohesion in zinc and copper. Both the positive sub-atoms and the negative electrons are passing from a region of lower into one of higher cohesion, and in so doing they are losing potential energy and gaining kinetic energy.

It follows from this point of view that a metal placed in a liquid of higher specific inductive capacity will become electronegative to the same metal in a liquid of lower specific inductive capacity. This has been shown experimentally by van Deventer and van Lummel,* though they offered a different interpretation of the phenomenon which they observed. By placing one piece cut from a rod of a given metal, as zinc, in a solution of sulphuric acid in water and another piece of the same rod in a solution of sulphuric acid in water and alcohol which was floated on the top of the water solution, the piece of metal in the alcohol became the positive pole of a voltaic cell, taking the place of copper in the Daniell's cell. In this experiment the piece of metal in the water solution gave off its positive sub-atoms faster than the piece in the alcohol solution, evidently on account of the higher specific inductive capacity of the water. By using two metals of nearly the same contact electromotive force, Messrs. van Deventer and van Lummel were able to invert the electrolytic polarity of several pairs of metals by putting the more electropositive metal (electropositive in the Voltaic series) in the alcohol solution.

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*Van Deventer and van Lummel, Zeit. phys. Chem., lxix, 136, 1909.

Charges of Electrolytic Ions.

It has been suggested in the preceding pages that the positive sub-atoms do not carry charges which are exact multiples of the electronic charge. This is contrary to the general assumptions of modern electrical theory and needs further consideration.

The belief that electropositive sub-atoms carry charges which are equal to or are simple multiples of the negative charge of an electron is a logical deduction from Faraday's laws and the notion of electrical neutrality which is involved in the two fluid theory. Faraday's discovery that the electrolytic separation of the combining weight of any univalent element from any compound was apparently associated with the liberation of the same definite quantity of positive or negative electricity led him to the conclusion that the ions which carry the current in electrolysis part with their charges at the electrodes. This view seems to make necessary the existence of unit positive charges as well as unit negative charges.

We now know, however, that this assumption of a unit positive charge is not necessary, since there is no known case where an ion gives off a positive charge in electrolysis, and we know very certainly that a current in a metallic conductor does not consist of positive and negative charges moving in opposite directions. In the case of the zinc and copper in a Daniell's cell, or in a solution of sulphuric acid, the zinc sub-atom escapes into the solution and sets free in the metal one or more electrons. The positive ions of the solution go to the copper plate and combine with one or more electrons. Neither ion in the solution gives off any electricity to either plate. The fact that a positive sub-atom can only set free or combine with some whole number of electrons does not tell us the magnitude of its positive charge unless we can show that this charge is totally neutralized by the electrons, and this we are unable to do.

The magnitude of the charge of a positive sub-atom has been directly measured in the case of only one element, that of the alpha particle, which has been shown to be the positive sub-atom of helium; but measurements of the magnitude of e/m for a number of positive ions given off by hot bodies have also furnished data from which the charges of the positive sub-atoms of these elements may be calculated. Rutherford and Geiger* and Regener** have measured the positive charge of alpha particles from Ra—C and Polonium and have found this charge to be, within the limits of experimental error, twice as great as the negative charge of an electron. Accordingly when an alpha particle combines with two electrons to form an atom of helium these atoms are as nearly as possible electrically neutral, as is shown by their low cohesion or affinity.

The only circumstances under which we have positive sub-atoms dissociated from their negative ions or electrons seem to be the following:

(a) The alpha particles in radioactive changes.
(b) The atomic ions in electrolysis.
(c) The positive ions spontaneously given off by some hot bodies.
(d) The ions of gas molecules dissociated by Roentgen rays or by flames or some other agency.
(e) The canal rays in the vacuum tube, if, indeed, these be positive sub-atoms.

The charge of the alpha particle has already been referred to. The gaseous ions produced by Roentgen rays or other agencies are supposed to become loaded with gas molecules so that their speeds in an electric field are less than they should be for the positive sub-atoms alone, though in the case of ions produced in flames, which will be considered later, it is possible to estimate roughly the charges on certain positive sub-atoms. The attempts to measure the charges on the separate particles in the canal rays have also given inconclusive results. Sir J. J. Thomson† has made many careful measurements on these rays, and he finds the maximum value of $e/m = 10^4$, but he finds particles giving every smaller value of this quantity down to zero. This suggests a relation to a recent investigation by Ehrenhaft‡ on the charges carried by very small particles of gold, silver and platinum produced in an electric arc. Ehrenhaft found these little particles to carry charges of all magnitudes from less than 10^{-10} up to 12×10^{-10}. He concludes from these results that there must be charges smaller than the charge of an electron. If it be granted, however, that the positive sub-atomic charges of the metal are not exact multiples of the electronic charge, these small residual charges may be accounted for.

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*Rutherford and Geiger, Proc. Roy. Soc. A, lxxxi, 141-162, 1908.

**Regener, Ber. D. Preuss, Akad. D. Wissen., July 22, 1909.

†Thomson, Phil. Mag., xviii, 821, Dec., 1909, xx, 752, Oct., 1910, and xxi, 225, Feb., 1911.

‡Ehrenhaft, Phys. Zeit., xi, 619, July 15, 1910.

A similar investigation by Przibram* on the charges carried by the particles in the fog produced by phosphorus gives a grouping of charges about values approximating to 4.7×10^{-10} and its multiples, as if the predominant charge were due to one or more electrons, but all kinds of values were obtained from 1.8×10^{-10} to 110×10^{-10}.

In the case of the positive ions produced in electrolysis we know only the magnitude of the negative charges which they may take from the cathode and their average velocity of drift through the liquid under the impulse of a known electric field. We do not know the resistance with which they meet in their movement through the solution, nor through what distances they travel between successive dissociations and recombinations. We know only that if all the ions of a given group have equal positive charges they are acted upon by the same force. If the speeds measured are assumed to be the maximum speeds which the ions can reach in the solution then the slower ions are slower because they are retarded more than the faster ones; but if they move through very short distances as free ions, then their velocity is an accelerated one, and the lighter ions should have the higher speeds. Any hypothesis which undertakes to explain their difference in speed on the basis of a resistance due to the surrounding water would seem to require that the ions having the smallest volumes should have the highest speeds. Thus the attempts which have been made to apply Stokes's equation to their movement would make their velocities vary inversely as their diameters, while, on the contrary, the larger ions of each group have the higher speeds.

On the other hand, if it be assumed that different sub-atoms have different charges, it is very easy to explain the differences in ionic velocities. We are not justified, however, in attempting to calculate the actual magnitudes of these atomic charges without knowing more about the phenomena which are involved in electrolysis. If it be assumed that the ions move very short distances between dissociation and recombination, their motion will be accelerated according to the well known equation, $F = ma$. Since the force acting upon an ion is proportional to its charge, if the ion met with no resistance its charge would be proportional to the product of its mass into its acceleration, and the charges of different ions would be relatively proportional to the products of their ionic masses into their ionic speeds.

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*Przibram, Phys. Zeit., xi, 360.

Whatever value may attach to this method of calculating the ionic charges, it leads to some interesting relations not hitherto observed. In the following table are given the hypothetical sub-atomic charges of three well marked groups of similar elements and of hydrogen calculated in this way. The ionic velocities are taken from Lehfeldt's tables. In the last column are given the ratios of the hypothetical charges of corresponding elements in different groups. It will be seen that for each pair of groups these ratios are constant within the limits of our knowledge of ionic speeds.

Element	Atomic Weight	Ionic Velocity	Ionic Charge	Ratio of Charges
Cs	133	78.8	10480	Cs/I= 1.07
Rb	85.5	78.6	6720	Rb/Br= 1.07
K	39	75.5	2945	K/Cl= 1.09
Na	23	52.6	1210	Na/F= 1.17
Li	7	42.6	298	
H	1	365	365	
I	127	77	9779	I/Ba= 1.04
Br	80	78.1	6248	Br/Sr= 1.06
Cl	35.5	75.1	2666	Cl/Ca= 1.07
F	19	54.4	1034	F/Mg= 1.02
Ba	137.4	68	9343	Cs/Ba= 1.12
Ca	87.6	67	5869	Rb/Sr= 1.14
Sr	40.1	66	2646	K/Ca= 1.11
Mg	24.3	46	1018	Na/Mg= 1.18

The above table indicates not only that the charge of the sub-atom increases when the atomic weight increases, but that it increases according to the same law in each group.

A. A. Noyes and his fellow workers* have shown that as the temperature increases the speeds of several of the electrolytic ions become more and more nearly equal, but he found almost as many cases where the opposite is true. If it could be shown that at the critical temperature of water the speeds of all the electrolytic ions become equal, it would indicate that the ionic charges calculated as above are proportional to the ionic mass. This, it will be shown, is not the case.

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*A. A. Noyes and others, Carnegie Institution Publications, No. 63, 1907.

ATOMIC CHARGES.

Positive Charges of Ions from Hot Metals.

A more direct method of measuring the charges of positive subatoms may be found in experiments carried out by Richardson and Hulbirt* on The Specific Charge of the Ions emitted by Hot Bodies. The authors assume that the ions all carry the same charge, but they give a number of experimental values of e/m which may be used to calculate the relative charges of the positive ions from a number of metals. The experimental difficulties of this investigation were great, and the agreement between the different values obtained for the same metal are not very satisfactory, but, as will be seen from the following considerations, the mean values determined for the different metals are probably not far wrong.

The values of e/m determined by Richardson and Hulbirt for six elements are shown below. Four other elements were used in the investigation, but the values obtained from them were not satisfactory to the authors. Thus two samples of iron gave values of 372 and 409, and the individual values for the same sample differed by more than 100%. Only one measurement was made on osmium. The values obtained for tantalum ranged from 115 to 253 and for tungsten from 47 to 541.

The values given below are those derived directly from the experiment. They were afterward multiplied by a constant to correct for the value of e/m obtained for the electron by the same method; but as the values used in the present paper are only relative this would not affect the result.

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*Richardson and Hulbirt, Phil. Mag., xx, 545, 1910.

The second column of the table contains the values of e/m taken from Richardson and Hulbirt's data, and the third column contains the relative values of e found by multiplying e/m by the atomic weight of the element.

Element	e/m	e	Element	e/m	e
Platinum	243	471	Gold	139 280	273 546
Palladium	212	225	Silver	215	232
Nickel	239	130	Copper	230	146

The elements are arranged in groups according to the periodic law, and it will be seen at once that the values of e for each group are distributed much as are the values of the ionic charges calculated from electrolytic data. It will also be seen that by multiplying the values obtained from electrolytic data by the factor three the two sets of values are made to correspond very closely. This is best shown by arranging both sets of elements according to their position in the periodic table. It was also observed that the charges calculated in this way are very approximately proportional to the square roots of the atomic weights. In the table given below, the number first given under the atomic symbol is the square root of the atomic weight and the second number is the relative atomic charge.

Atomic Charges and Square Roots of Atomic Weights.

H 1 11	Li 2.5 9.			
F 4.4 31.	Na. 4.8 36.	Mg 4.9 30.		
Cl 6. 80.	K 6.2 88.	Ca 6.3 79.	Ni 7.6 130.	Cu 8.— 146.
Br 9. 188.	Rb 9.25 202.	Sr 9.4 176.	Pd 10.3 225.	Ag 10.4 232.
I 11.3 293.	Cs 11.5 314.	Ba 11.7 280.	?	?
			Pt 14.— 471	Au 14.+ 546.& 273

This relation is shown more strikingly in Curve I, Plate I, where the atomic charges calculated by the two methods are plotted as abscissas and the square roots of the atomic weights as ordinates. It will be seen that the agreement of the values calculated by the two methods is very close except in the case of gold, where one of Richardson's values lies on each side of the expected value, and of platinum. Strictly speaking, the elements of each group lie on a curve of their own,* but these group curves are parallel and very close together.

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*It should be remembered in this connection that the charges of the halogen group were calculated from the velocities of negative ions. They should properly be represented on a branch curve for which the values of the atomic charges are negative. This curve would be perfectly symmetrical with the curve given.

If the quantities calculated by Richardson and Hulbirt for values of e/m are what they were supposed to be, it follows that positive subatoms have different characteristic charges which are closely proportional to the square roots of their atomic weights. It also seems to follow that the ions in electrolysis move with accelerated velocities through very small distances between dissociation and recombination.

Charges of Monatomic Gas Molecules.

A method which may be used for estimating, at least roughly, the charges of gas molecules is found in the assumption that cohesion must be at least approximately proportional to the molecular charges. In a paper by W. Sutherland* on the Viscosity of Gases and Molecular Force is given a method of calculating the cohesion between gas molecules from the viscosity of the gases and the laws of the kinetic gas theory. Rankine† has recently measured the viscosity of the gases of the argon group, and has calculated from his data and Sutherland's equation the magnitude of Sutherland's cohesion factor, C, for these gases. His values are as follows: Helium, 70; Neon, 56; Argon, 142; Krypton, 188; Xenon, 252. He calls attention to the evident misfit of helium in this series, since from its low critical temperature it should have much less cohesion than any of the other gases. He finds in the case of the other gases that the ratio of the critical temperature (absolute) to the cohesion factor is about 1.12. By calculating C from this ratio for helium it is found to have a value of about three instead of seventy.

If it be assumed that cohesion is proportional to the atomic charge in these monatomic molecules, then the factor C should be proportional to the square roots of the atomic weights, which it is within the limits of experimental error.‡

Atomic Charges and Solubility.

A similar relation between the same gases is shown in their solubility in water. A. v. Antropoff§ has determined the solubility of the above gases in water at different temperatures. For 20 degrees his numbers are as follows: He, .0138; Ne, .0147; Ar, .0379; Kr, .0729; Xe, .1109. The relation between this solubility factor and Sutherland's cohesion factor is apparent at a glance. This is to be expected, since the solubility should be a measure of the cohesion between the gas molecules and water. It will be seen that these solubility factors are also, within the limits of experimental error, proportional to the square roots of the atomic weights, helium, as before, being an exception.

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*Sutherland, Phil. Mag., xxxvi, 507, 1893.

†Rankine, Physik, Zeitsch, xi, 746, Sept., 1910.

‡Since this paper was in the hands of the printer I find an article by Rankine in the Phil. Mag. of Jan., 1911, p. 45, in which he also relates the viscosities of the gases of the Argon group to the square roots of their atomic weights.

§v. Antropoff, Roy. Soc. Proc., A, lxxxiii, 474, Apr. 14, 1910.

In Curve II, Plate II, the values of Sutherland's cohesion factor as calculated by Rankine and the values of v. Antropoff's solubility factors are plotted as abscissas against the square roots of the atomic weights as ordinates. The solubility factors have been multiplied by the constant 3 x 10^3 to bring them on the same diagram as the other factors. The points for the cohesion factors are represented by large circles and for the solubility factors by small, black circles. The curve is drawn for v. Antropoff's solubility factors. Helium is seen to depart from the law in the same manner in both cases. If its cohesion factor be used as calculated by Rankine from its critical temperature, it falls directly upon the curve for this factor.

It will be seen that the curve drawn cuts the axis of ordinates at nearly the same point as does Curve I. Accordingly the atomic charges of the elements may be calculated from either curve by using the equation $e = (\sqrt{w} - a)\ k$, where w is the atomic weight and a is a constant between three and four. The same equation with approximately the same constant may be used to calculate the values of Sutherland's cohesion factor.

The above relations seem to the writer to make the conclusion inevitable that gaseous solubility in water is proportional to the cohesion of the gas molecules for the water molecules, and that this cohesion is proportional to the atomic charges, when the gases are monatomic. In the case of gases having compound molecules the same law would probably hold except that the cohesion would be proportional to the residual molecular charge. Hence gases having high critical temperatures should be more soluble than gases having low critical temperatures.

It is interesting in this connection to note that Traube* and Kleeman† have calculated that the valency of an atom is proportional to the square root of its atomic weight. In the paper referred to, Kleeman calculates the value for a number of atoms of a constant Ca which determines the surface tension of the liquid to the molecules of which the atoms belong. This constant depends only upon the nature of the atoms, and is proportional to the square root of the atomic weights. This would seem to make chemical valency as well as cohesion vary directly as the atomic charge.*

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*Traube, Physick. Zeitsch., x, 667, Oct., 1909.

†Kleeman, Phil. Mag., xix, 784, May, 1910.

Charges of Atomic Ions in Flames.

A condition analogous to the discharge of ions by hot bodies may be found in the dissociation of some metallic salts in a flame. When salts of the alkali metals are dissociated in a Bunsen flame, the outer cone of the flame is colored by the positive ions. T. P. Irving† has shown that when the outer cone is well separated from the inner part of the flame it may sometimes be strongly deflected toward the negative side of an electric field, showing definitely the electropositive character of the ions which give the color to the flame. Irving determined the order of the relative deflection of the ions of different metals in a given electrostatic field. In the case of the ions of the alkali group, which seem most certainly to be dissociated into positive sub-atoms and electrons, he found the order of deflection to be caesium, rubidium, potassium, sodium, lithium. In this experiment, where the ions were most certainly the positive sub-atoms of the metals with all possibility of hydration excluded, the order of deflection is that indicated by the atomic charges of the metals as calculated above, and is the inverse of what it should be if the ions carried equal charges.

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*Since this paper was ready for the printer I have been able to calculate the compressibilities of a large number of elements from the formula $c = (\sqrt{w}-a)k$, the constants a and k varying from group to group, though for several groups a has a value of approximately 3.6. In the electronegative elements the equation takes the form $c = (a-\sqrt{w})k$; that is, the compressibility decreases as the negative charge of the element increases. This would be expected from the fact already mentioned that the more electronegative a metal is in the voltaic series the greater is its cohesion.

I have also been able to calculate the approximate melting points of a considerable number of elements from simple formulae in which the square root of the atomic weight is one factor. Thus the approximate melting point of the alkali metals may be calculated from the formula $(T-a)\sqrt{w} = k$, where T is the melting point (absolute) of the element and a and k are constants for the group. If a=252.5 and k=531.5 the calculated values of the melting points will vary on the average only .8 of one per cent from the experimental values.

The atomic refraction as calculated by Edwards (Am. Chem. Jour., vols. 16 and 17) and by Eisenlohr (Zeit. phys. Chem. LXXV, 585, Dec., 1910), also varies as the square roots of the atomic weights of the elements. No doubt this constant will be found to be an important factor in calculating many other properties of the elements.

†Irving, Phys. Rev., xxix, 248, 1909.

The same order also holds in the conductivities of the metallic vapors of this group. The conductivities of flames containing vapors of the metals of this group are given as follows: Caesium, 116; rubidium, 82; potassium, 64; sodium, 8.5; lithium, 2.5.

Atomic Charges and Chemical Valence.

Further arguments against the equality of sub-atomic charges may be found in the phenomena of chemical valence. The writer of this paper, not being a chemist, approaches this part of the argument with a full appreciation of his liability to err from lack of familiarity with the phenomena under consideration. In order to make this liability as small as possible, the discussion will be confined to a few of the phenomena of chemical valence which were quoted by Richard Abegg in his celebrated paper entitled Die Valenz und das periodische System.* This selection of phenomena seems all the more suitable for the reason that it was made for the purpose of substantiating an entirely different theory of chemical valence.

As has already been stated several times, the point of view of this paper is that all molecules are made up of electropositive sub-atoms held together by their mutual attractions for the same electron or group of electrons. When a molecule dissociates, the more positive sub-atom holds an excess of the connecting electrons and becomes the negative ion. Thus the hydrochloric acid molecule is presumably made up of two sub-atoms, one of hydrogen and one of chlorine, held together by their mutual attraction for one or more detachable electrons. When they dissociate the chlorine always takes the connecting electron or excess of electrons, if there be more than one, hence it must be the more positive sub-atom; otherwise the attraction between it and the electron would be less than the attraction between the hydrogen sub-atom and the electron.

In the following discussion the propositions regarding valence which are italicised are quoted from Abegg's paper.

All atoms have a definite higher limit to their valency. This will be true if an atom is a positively electrified body attracting to itself negatively charged electrons, whether its positive charge is some opposite multiple of the electronic charge or not. In any case, after taking on a sufficient number of electrons the system will become negatively electrified and will then repel negative and attract positive charges.

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*Abegg, Zeit. Anorg. Chem., xxxix, 330, 1904.

The valence of an element in a compound depends upon the nature of the other component. It is difficult to see how this can be true unless the other components have different electrical charges. If they have equal charges, the same number of their atoms should be held by the charge of the atom under consideration. Where more than one compound may exist between atoms of only two kinds, as in the oxygen and nitrogen series, it would seem that the opposite charges of the two constituents are neither equal nor is one an exact sub-multiple of the other.

All elements vary gradually from each other in their electric affinity. In this statement, gradually apparently does not mean step by step, as they necessarily would vary if they all carried unit elementary charges or multiples of these charges.

In cases where the same element comes out of a compound in several electrovalence steps, the affinities of the higher valencies are generally weaker than the lower. This is shown, according to Abegg, in the fact that the heat of chemical reaction per equivalent is always greater for the lower steps than for the higher. Thus $FeCl_3$ and $FeCl_2$, $PbCl_4$ and $PbCl_2$, etc. The preparation of practically pure compounds of a determined valence step, as for example of $FeCl_2$ without the accompaniment of $FeCl_3$ shows how enormously different the affinity of the two valence steps must be.

The formation of the higher combination steps, that is to say, the taking up of new valence charges is the more difficult the more charges have already been taken up.

The above propositions from Abegg's paper express exactly the conditions which would prevail from the assumption of the attraction for detachable electrons being the cause of valency. Thus if an electrically charged body have several bodies with electrical charges opposite to its own and equal to each other brought successively into its electrical field, each successive charge will be attracted by a weaker force than its predecessor; while in removing them each successive one will be held by a greater force than the one which preceded it.

The same element may have either a positive or a negative valency. This phenomenon is so well known that no examples need be given. Abegg refers especially to the compound ICl. Here is a compound made up of two atoms both of which may have negative valencies when combined with a metal, yet this compound dissociates in water and the products of its hydrolysis are HCl and IOH. Here the chlorine has taken the negative valence and combines with a positive hydrogen sub-atom, while the iodine replaces a positive sub-atom in the water molecule. Evidently if the chlorine had not had a stronger attraction for the detachable electron than had the iodine it would not have retained it.

Abegg gives hydrogen, boron, silicon, phosphorus, arsenic, antimony, sulphur and iodine as elements which may certainly take either positive or negative valencies according to the element with which they are combined.

The greater the atomic weight of an element in a group the stronger is its positive valence. This is equally true if stated, the greater the atomic weight of an element in a group the more electropositive it is in the voltaic series, and it has already been shown in this paper how the relative charges of the elements in a group may be calculated. Abegg gives many examples of this law. Thus, in the case of nitrogen and phosphorus, nitrogen, the lighter element, can hold only three atoms of chlorine with their attached electrons while phosphorus can hold, though in an unstable condition, five. Oxygen may have in unstable compounds a positive valence of four and sulphur of six. Oxygen is itself negative to sulphur in di-oxide and tri-oxide compounds. Iodine as a positive ion forms with the elements of its own group the compounds IF_5, ICl_3, IBr. Bromine, being less positive, can form the compounds BrF_3, BrCl. Another fact referred to by Abegg which shows the difference in the tenacity with which the elements of this group hold to their valence electrons is shown in the weakening of the affinity of their gas molecules at high temperatures. Thus at high temperatures the iodine molecule dissociates completely, bromine partly, chlorine appreciably and fluorine scarcely at all. This seems to indicate that the charge of the connecting electron or electrons is approximately equivalent to the charges of both fluorine atoms, while in the other elements of the group the positive charge of a single atom becomes more and more nearly equivalent to the negative electronic charge as the atomic weight increases; accordingly the residual charge which constitutes cohesion is greatest for iodine and least for fluorine. Hence iodine is a solid at ordinary temperatures, bromine a liquid, chlorine an easily liquifiable gas and fluorine a relatively permanent gas.

ELECTROMAGNETIC PHENOMENA.

The Electromagnetic Field.

The magnetic effects of an electric current have long been known and the quantitative relations between a current and a magnetic field are well understood, but at the present time no physical theory which will account for these relations has ever been advanced. The fundamental phenomenon seems to be the attraction between two parallel currents in the same direction, and no explanation of this phenomenon seems to be forthcoming. In this respect the present paper does not differ materially from its predecessors. The theory of electric action which has been here outlined does, however, offer certain suggestions which may be worth considering.

A current in a metallic conductor seems to be entirely due to the passage of electrons along the conductor, while in an electrolytic solution it seems to be due to the drifting of both positive and negative ions, though, on the whole, to the positive ions; yet the magnetic effect of a given current seems to be the same in both cases.

That a magnetic field can be produced by the motion of electrical charges has been proved conclusively by Rowland and his students. Since the only phenomenon which we know accompanies an electric charge is an elastic strain in the ether, the magnetic field is apparently due to the motion of these fields of strain through the ether. The preceding discussion has seemed to show that both the electrons in a conductor and the ions in an electrolytic solution are passed along in a succession of periodic flights from one molecule to another. While the electron or ion is associated with an opposite charge in an atom or molecule it can have little, if any, external electric field. While it is moving from one atom to another it will have an external electric field, and since we know of nothing else to produce the magnetic field of a current, we must suppose it to be due to the motion of these short-lived electric fields.

Around a conductor carrying a current these electric fields will spread out with the velocity of light, and their centers of strain will advance with the velocity of an electron in its flight. What this velocity is we have no means of knowing, since we can on any assumption calculate only its average velocity, and we have no means of knowing what part of the time it is at rest. If all the electrons of a given cross section of the conductor advance together, as has been shown to be probable, then these advancing electric fields form closed loops about the conductor and follow each other at regular intervals. It is easy to see from this view how two parallel currents in opposite directions must repel each other, since these waves going in opposite directions would have to pass through each other, and at such times the amplitude of the strain would be twice as great and the energy of the two sets of waves four times as great as of a single set. It is not so easy to see how two parallel currents in the same direction attract each other. If the waves of the two currents succeed each other at intervals of a half wave length they will, however, attract each other, since there would then be less potential energy of displacement in the ether between the currents than in the ether outside of them, and the reaction to this strain would force the currents toward each other.

Magnetism in Iron.

The question as to how the ether waves considered above would affect a magnet depends upon our theory of magnetism. Here there is substantial agreement upon a few points. The molecular theory of magnetism seems to be unquestioned. Ewing has satisfactorily accounted for the magnetic properties of iron on the assumption that these molecules are persistent and are oriented by their magnetic attractions and repulsions for each other; accordingly that a bar of iron is made an electromagnet by simply having its molecules rotated into a definite orientation.

The only magnetic molecule we know how to construct is one on the pattern of Rowland's rotating disc. Thus a molecule consisting of a number of electrons moving in a more or less circular orbit in a common plane about a positive atom would be such a disc magnet. The Zeeman phenomenon indicates that in some molecules the electrons are moving in broadly elliptical or circular orbits. The spectra of the elements indicate that some molecules have a very large number of electrons capable of vibrating or rotating under the influence of a central force. These spectra also show that iron has the greatest number of these oscillating electrons, nickel next and cobalt next to nickel.

Such a system of rotating electrons would set up a series of rotating strains in the ether following each other around the atom at definite intervals. This condition is strictly analogous to the assumed condition along a wire carrying a current. The waves produced by these rotating electrons travel in opposite directions on opposite sides of the molecule. In a magnet, when these molecular systems are all faced in the same direction and the planes of rotation of their electrons are perpendicular to the magnetic axis, the surface currents produced by their electronic systems are all flowing in the same direction around the magnet. Over the surface of the magnet there is accordingly a series of successive, temporary electric fields moving around the magnet, which are strictly analogous to the temporary electric fields moving along a wire which is carrying a current. Accordingly, if lines of magnetic force are assumed lengthwise along a magnet there must be similar lines of magnetic force encircling a current.

The condition inside a solenoid would then be similar to the condition inside a magnet, except that it would be much less intense. Both regions would be filled with rotating electric fields. The proof of a similar rotation in the two cases is shown in the rotation of the plane of polarization of light. These rotating strains forming a series of vortex waves around the magnetic axis would extend out from both ends of the magnet and solenoid, and would spread through the ether with the velocity of light. When they met and formed closed loops these loops would contract, because the shorter they became the less the potential energy of strain in the ether. These vortex lines from opposite poles of a magnet would accordingly attract each other, while from like poles they would repel each other, like parallel currents in opposite directions.

The position of normal equilibrium of the magnetic molecules in iron would apparently be such that electrons between them would move in the same direction and follow each other, while the condition of magnetic saturation would be unstable, since the electronic fields would move in opposite directions between the molecules and thus increase the strain in the intervening ether.

For the same reason, a magnet in the vicinity of a current would set itself so that the electrons on the side toward the current would be moving in the same direction as those of the current.

The above short discussion of magnetism can be regarded as little more than a suggestion. It is offered in the hope that it may aid in clearing up some of the fundamental difficulties.

APPENDIX.

Note On the Electrical Theory of Benjamin Franklin.

There seems to be a general misunderstanding regarding Franklin's theory of electricity. Smyth, in his *Life and Writings of Benjamin Franklin,* Vol. 1, p. 96, quotes with apparent approval Garnett's *Heroes of Science* as saying of Franklin's views, "They are perfectly consistent with the views held by Cavendish and Clerk Maxwell, and though the phraseology is not that of modern text books, the statements themselves can hardly be improved upon today." Maxwell, in his *Electricity and Magnetism,* Vol. 1, p. 41, describes the one fluid theory of Electricity as follows: "In the theory of One Fluid everything is the same as in the theory of Two Fluids except that, instead of supposing the two substances equal and opposite in all respects, one of them, generally the negative one, has been endowed with the properties and name of Ordinary Matter, while the other retains the name of the Electric Fluid. The particles of the fluid are supposed to repel one another according to the law of the inverse square of the distance, and to attract those of matter according to the same law. Those of matter are supposed to repel each other and attract those of electricity."

Sir Oliver Lodge says on page 202 of his book, entitled *Electrons*: "The positive electron has not, so far as I know, been as yet observed free. Some think it cannot exist in a free state, that it is in fact the rest of the atom of matter from which a negative unit charge has been removed; or, to put it crudely—that 'electricity' repels 'electricity' and 'matter' repels 'matter,' but that Electricity and Matter in combination forms a neutral substance which is the atom of matter as we know it. Such a statement is an extraordinary and striking return to the views expressed by that great genius, Benjamin Franklin."

It is only fair to Sir Oliver Lodge to assume that he has not read Franklin's papers on Electricity, as otherwise he could not have made such a misleading statement in regard to his theory. The other writers who have been quoted as referring to Franklin's electrical theory may not have appreciated the fundamental difference between it and the one fluid theory described by Maxwell, but the author of *Modern Views of Electricity* could scarcely have failed to be impressed with this difference in even a perfunctory reading.

In a paper entitled *Opinions and Conjectures, Concerning the Properties and Effects of the Electrical Matter, etc.,* sent by Franklin to Peter Collinson under date of July 29, 1750, he discusses the nature of the electrical matter which he had previously spoken of as the electrical fire. As this was written at the close of his electrical experiments, three years after he had first proposed the theory of a single electricity, it evidently states his mature views. The first five paragraphs of his discussion are as follows:

"1. The electrical matter consists of particles extremely subtile, since it can permeate common matter, even the densest metals, with such ease and freedom as not to receive any perceptible resistance.

"2. If any one should doubt whether the electrical matter passes through the substance of bodies, or only over and along their surfaces, a shock from an electrified large glass jar, taken through his own body, will probably convince him.

"3. Electrical matter differs from common matter in this, that *the parts of the latter mutually attract* (the italics are mine), those of the former mutually repel each other. Hence the appearing divergency in a stream of electrified effluvia.

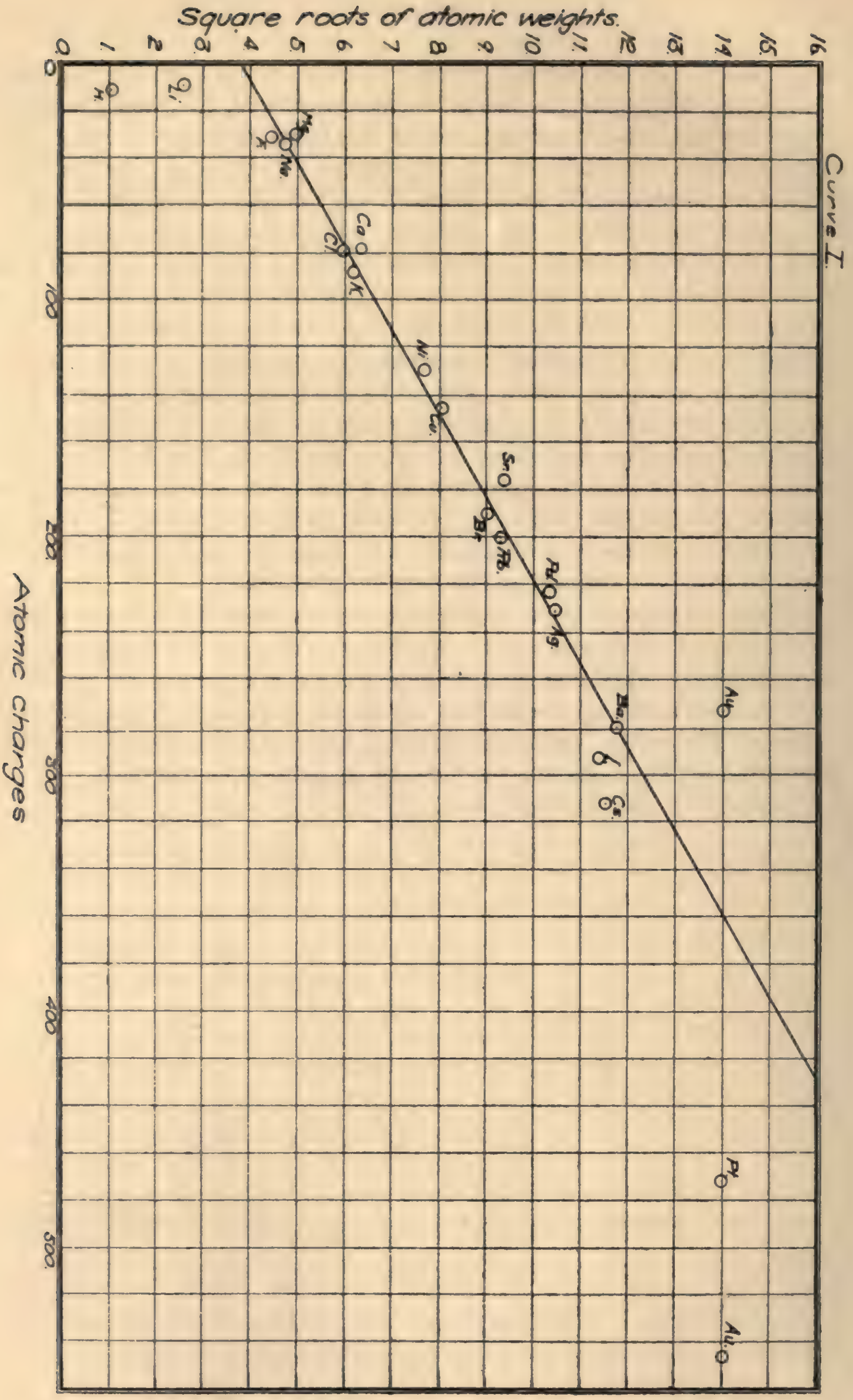
"4. But though the particles of electrical matter do repel each other, they are strongly attracted by all other matter.

"5. From these three things, the extreme subtility of the electrical matter, the mutual repulsion of its parts, and the strong attraction between them and other matter, arise this effect, that, when a quantity of electrical matter is applied to a mass of common matter, of any bigness or length, within our observation (which hath not already got its quantity) it is immediately and equally diffused through the whole."

Neither in these paragraphs nor in any other of Franklin's electrical papers have I been able to find any suggestion of the notion that electrical matter and common matter "are equal and opposite in all respects" or that there is such a phenomenon as the "neutralization" of electrical charges, or of electrical matter and common matter. Franklin everywhere speaks of the earth and bodies upon its surface as having a common stock of the electrical fire or electrical matter. In his view, an unelectrified body is one in which the electrical fluid is in equilibrium with that in the earth. A positively electrified body is one in which this fluid has been compressed, and a negatively electrified body is one in which it has been rarefied. This is well shown in a letter to Peter Collinson, dated July 11, 1747. After speaking of two men standing on wax and electrifying themselves, one from a glass tube and the other from the rubber, while a third man stands on the floor near them, he says, ''These appearances we attempt to account for thus: we suppose, as aforesaid, that electrical fire is a common element, of which every one of the three persons above mentioned has his equal share, before any operation is begun with the tube. A, who stands on wax and rubs the tube, collects the electrical fire from himself into the glass; and his communication with the common stock being cut off by the wax, his body is not again immediately supplied. B (who stands on wax likewise), passing his knuckle along near the tube, receives the fire which was collected by the glass from A; and his communication with the common stock being likewise cut off, he retains the additional quantity received. To C, standing on the floor, both appear to be electrified: for he having only the middle quantity of electrical fire, receives a spark upon approaching B, who has an over quantity; but gives one to A, who has an under quantity. If A and B approach to touch each other, the spark is stronger, because the difference between them is greater; after such touch there is no spark between either of them and C, because the electrical fire in all is reduced to the original equality.''

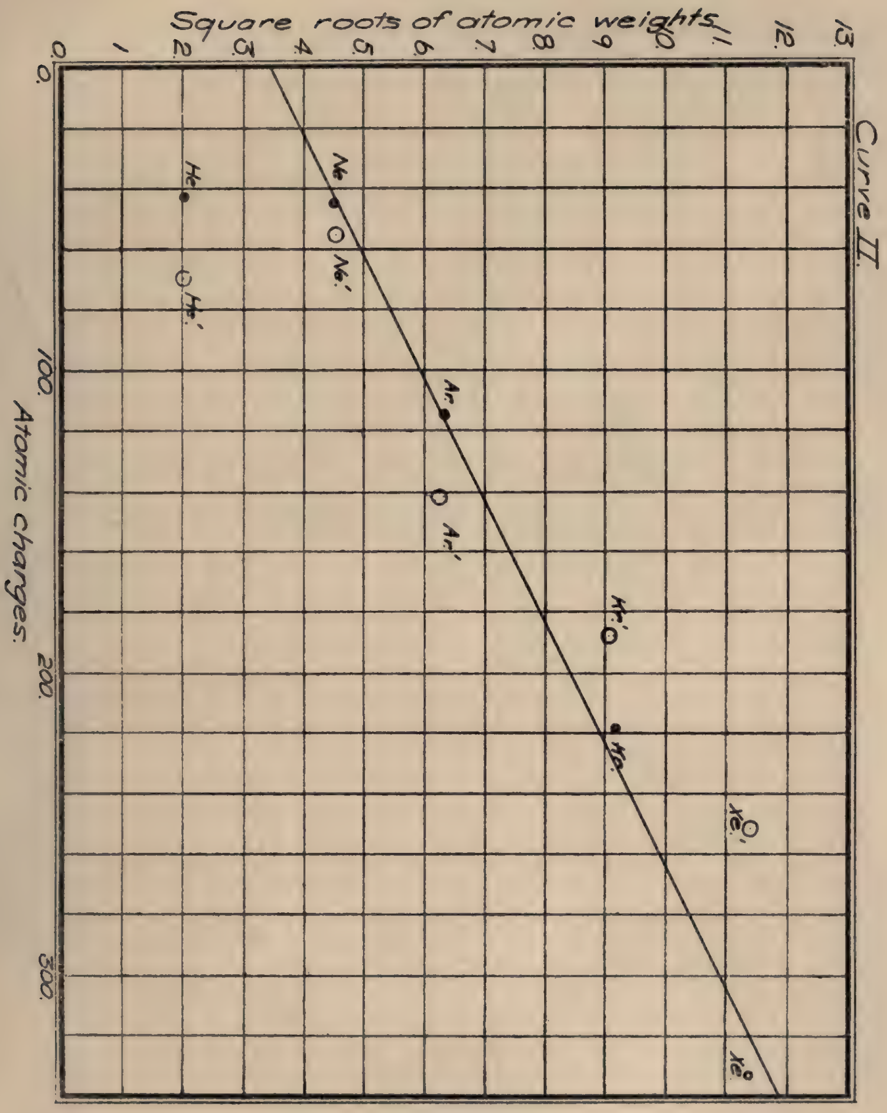
These quotations seem to make it certain that Franklin regarded the earth and all bodies on its surface as being at all times charged with electricity, and that an insulated body was regarded as electrified only when its electrical charge was not in equilibrium with the electrical charge of the earth. In this respect his one fluid theory is fundamentally different from the one fluid theory as defined by Maxwell.

PLATE I.



Square roots of atomic weights.
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Curve I.
Atomic charges
100
200
300
400
500
H
Li
Mg
Al
Na
Ca
Cl
K
Ni
Cu
Sn
Br
Rb
Pd
Ag
Ba
Cs
Au
Pt
Au

PLATE II.


Square roots of atomic weights
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Curve II.
Atomic charges.
0.
100.
200.
300.
He
He'
Ne
Ne'
Ar
Ar'
Kr
Kr'
Xe
Xe'

126888 Physics
Elect.

Author Sanford, Fernando

Title A physical theory of electrification.

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